FINAL REPORT

Effects of changing wildfire management strategies

JFSP PROJECT ID:17-01-03

September 2021

Dr. Jose Iniguez
USDA Forest Service

Dr. Andrea Thode
Northern Arizona University

Dr. Sarah McCaffrey
USDA Forest Service

Dr. Alexander Evans
Forest Stewards Guild

Dr. Marc Meyer
USDA Forest Service

Shaula Hedwall
US Fish and Wildfire Service

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Government.

Contents

Abstract 4
Key Findings 4
Photographs 5
Project Overview 5
Overall Objectives 5
Background 5
Objectives 1 7
Materials and Methods 7
Results and Discussion 10
Conclusions (Key Findings) and Management Implications 15
Objectives 2 16
Materials and Methods 16
Results and Discussion 18
Conclusions (Key Findings) and Management Implications 22
Objective 3 23
Methods 23
Results and Discussion 24
Conclusions (Key Findings) and Management Implications 27
Objective 4 28
Overall Conclusions (Key Findings) and Management Implications 29
Literature Cited 30
Appendix A: Contact Information for Key Project Personnel 36
Appendix B: List of Scientific/Technical Publications/Science Delivery Products: 38

List of Tables

N/A

List of Figures

Figure 1. Number of large wildland fires (>40.5 ha) and area burned (ha) by dominant strategy from 2002 to 2016 in the western US.

Figure 2. Number of large wildland fires (>40.5 ha) and area burned (ha) by dominant strategy from 2002 to 2016 for each subregion.

Figure 3. Mean discovery and control dates for large 'suppression' and 'other' fires (40.5 ha) in the western US.

Figure 4. Map of the study region in Arizona and New Mexico, USA showing location of the 735 large fires (> 404 ha) in this study that burned between 1984-2017.

Figure 5. Boxplots showing spatial pattern metrics of high-severity burn patches as a function of fire management strategy.

Figure 6. Relationship between fire size (burned area) and high-severity spatial pattern metrics stratified by suppression fires (red) and managed fires (blue).

Figure 7. Relationship between percent high-severity fire and spatial pattern metrics of high-severity burn patches stratified by suppression fires (red) and managed fires (blue).

Figure 8. Comparison of full suppression and managed wildfires based on (a) distance to wilderness (b) distance to WUI and (c) percent high severity within the entire study area which included the Southwest (Arizona and New Mexico) and California

Figure 9. Comparison of managed wildfire between California and the Southwest based on (a) distance to wilderness (b) distance to WUI and (c) percent high severity

Figure 10. Comparison of managed fires in California before (2002-2008) and after (2009-2016) the 2009 policy guidance based on (a) distance to wilderness (b) distance to WUI and (c) percent high severity.

Figure 11. Number of land management agencies involved per managed wildfire compared before and after the 2009 policy guidance in (a) California and (b) Southwest.

Figure 12. Figure 12. Frequency of positions for individuals interviewed as part of the social aspects on managed wildfires.

List of Abbreviations/Acronyms:
SRD: sharp regression discontinuity
SIT-209: Situation report
ICS-209: Incident Status Summary
RAWS: Remote Automated Weather Stations
PSA: Predictive Service Areas
WFDSS: Wildland Fire Decision Support System
RdNBR: Relativized differenced Normalized Burn Ratio
dNBR: differenced Normalized Burn Ratio
RBR: Relative Burn Ratio
GEE: Google Earth Engine
MTBS: Monitoring Trends in Burn Severity
CBI: Composite Burn Index
WFU: Wildland Fire Use
US DOI: United Stated, Department of Interior
USDA: United Stated Department of Agriculture
GYRATE_AM: area-weighted mean radius of gyration
PARA_AM: area-weighted mean perimeter area ratio
PLADJ: percentage like adjacencies
CA: Class area
SDC: Stand-replacing Decay Coefficient
ANOVA: Analysis of Variance
OLS: ordinary least squares
HRV: Historical Range of Variability
VPD: Vapor Pressure Deficit
WUI: Wildland-Urban Interface
SILVIS: Landuse dataset
SMA: Surface Management Agency
ECDF: Empirical Cumulative Distribution Function
SW: Southwest
CA: California
DDF: Discrete Distribution Function
PNF: Prescribed Natural Fire
MFDF: Managed Fire Decision Framework

Keywords: resource objective fires, managed wildfire, wildfire duration, wildfire weather, high burn severity, WUI, wilderness, social barriers to managed wildfire, multijurisdictional wildfire

Acknowledgements:
The authors would like to thank Joint Fire Science Program for funding this project as well as our institutions for their support including the Rocky Mountain Research Station (particularly the Grants and Agreements team), the Forest Stewards Guild, and the Northern Arizona University.

Abstract

Managed wildfires, naturally ignited wildfires that are managed for resource benefit, have the potential to reduce fuel loads and minimize the effects of future wildfires, but have been utilized mainly in remote settings. A new policy federal guidance in 2009 provided greater flexibility for using this tool with the effects of the 2009 changes still not fully understood. In summary, we found that managed wildfires are significantly different and a preferable ecological option to full suppression wildfires mainly due to the reduced high severity proportion and smaller high severity patches. The reduced negative affects associated with managed wildfires are related to the docile weather conditions in which these wildfires burn, mainly after the peak wildfire season. Despite the benefits of managed wildfires, our Western U.S. analysis found that although the number of managed wildfires has increased since 2009 the overall area burned has not significantly changed prior to and following the 2009 policy guidance, particularly in California. However, these managed wildfire patterns vary within the western U.S. Similarly, the majority of managed wildfires are still burning in or close to wilderness areas and away from the wildland urban interface (WUI). Therefore, although the 2009 Guidance has promoted greater use of this fuel reduction tool, the total area burned and location of these treatments have not significantly changed. This suggests that the 2009 policy guidance alone did not alter the overall problem of high fuel loads and homogeneous landscape conditions that continue to facilitate large destructive wildfires across the western US. A review of existing research and preliminary analysis of interviews from 2021 fires indicates that barriers to decisions to authorize a managed wildfire include both environmental and social factors. Environmental factors include burning conditions including weather and fuel conditions. Social factors include internal factors such as agency support and resources and external factors such as perceived public pressure to suppress.

Key Findings

The *2009 Policy Guidance* led to an estimated 53-73% increase in the number manage wildfires, with the most notable increases in the Inland Empire, Rocky Mountains and Southwest regions, however, this not necessarily translate to greater area burned.

Managed wildfires tend to burn longer (52 to 11 days for suppression fires), later in the year and during more docile weather conditions, which results in lower percent high severity. In contrast, high severity burn patches in full suppression fires had greater area, reach, aggregation, total core area, were simpler in shape, and decayed slower than patches in managed fires.

Managed and full suppression wildfires are also distinctly different in terms of where they burn. Strategies to manage wildfires for resource benefits are used in remote wilderness areas further from WUI, usually involve a single agency. Moreover, although these geographic characteristics also vary by region they have not changed before and after 2009.

Barriers to managed wildfire are dominated by environmental (burning conditions) as well as social factors including both internal (institutional) and external (public pressure).

Photographs

Uploaded to the JFSP website

Project Overview

In 2009, new federal guidance for wildland fire management expanded the range of options for managers working to reduce the threat of high intensity wildfire, improve forest health, and respond to a changing climate. A key element of the guidance provided greater flexibility to use naturally ignited wildfire as a tool for achieving multiple resource objectives. In some areas, managers have been using multiple wildfire management strategies to effectively achieve their goals, but overall, the use and impact of new options are not well understood. New research is needed to understand how wildfire response has changed and its effects on natural resources.

Overall Objectives

After examining available resources and previous work, we modified the original objectives into the following our objectives that were addressed in four individual studies each of which has been or will be published in a peered review journal. The objectives included:

1. To explore a) what effect, if any, the *2009 Policy Guidance* had on the strategic response to wildland fires, and to what extent individual fires changed in terms of management duration and area burned and b) what effect, if any, the *2009 Policy Guidance* had on total area burned over the course of a fire season.
2. To assess whether spatial patterns of high-severity patches differed between managed and full suppression wildfires.
3. To identify differences in proximity to wilderness, proximity to WUI, multijurisdictional management, and burn severity across (a) suppression strategies (managed versus full suppression and (b) time (before and after 2009).
4. To identify the key social barriers and facilitators to changing wildfire management strategies and the perceptions regarding effects to high-value resources.

After examining the available resources and previous work on this topic, we modified our original second and third objectives. We broadened our second objective to focus on high-severity wildfire because it is the main driver of impacts on high-value resources. Our third objective remained focused on factors that influence wildfire management strategy by focusing on wilderness, WUI, multijurisdictional management, and burn severity.

Background

Large high-intensity wildfires are one of the central land management challenges across the western United States (North et al 2021, Schoennagel et al. 2017). The increase in fire severity and area burned by wildfires observed over recent decades is likely to continue as the climate warms and dries (Abatzoglou and Williams 2016, Mueller et al 2020). To meet the growing fire management challenge, the pace and scale of fuel reduction treatments need to increase (North et al. 2012, Haugo et al. 2015, Stephens et al. 2016). Managers have two main fuel treatment options: mechanical thinning and wildland fire. While thinning treatments offer precise restoration to a desired forest structure that will minimize the probability of severe fire,

such treatments also tend to be costly (Hunter and Robles 2020) and are limited by biological, legal, administrative, and operational constraints (North et al. 2015). Moreover, many mechanical treatments must be combined with fire to be meet objective and be most effective (Kalies et al 2017; North et al. 2021). Since mechanically treating entire landscapes is not possible, managers have increasingly used fire as a restoration tool (Hunter et al. 2014). While prescribed fire is an effective tool for changing wildfire behavior, factors like air quality, resource constraints, liability concerns, and short prescription windows limit its use (Miller et al. 2020, Yoder et al. 2004, Williamson 2007). Another option for reducing fuels and improving forest health at landscape scales is the management of natural ignitions for resource benefit (Huffman et al. 2020).

In 2009, the *Guidance for Implementation of Federal Wildland Fire Management Policy* expanded the response options for wildfire management allowing a naturally ignited wildland fire to "be concurrently managed for one or more objectives and objectives can change as the fire spreads across the landscape" (Fire Executive Council 2009 p. 7). This guidance provided wildfire managers greater flexibility and more opportunities to use natural ignitions to reduce fuels, improve forest health, and allow fire to play its natural role across the landscape. Throughout this study, wildfires managed to meet resource objectives with strategies other than full suppression are referred to as either "Other strategies" or 'managed wildfires' in contrast to wildfire managed with a full suppression strategy (i.e., 'full suppression wildfires').

Modern use of natural ignitions to achieve management goals can be traced back to the late 1960's Prescribed Natural Fire program which was successfully implemented in some National Parks and wilderness areas where mechanical treatments were not a viable option (Hunter et al. 2014; van Wagtendonk 2007). Research from fires in the southwestern US suggests managed fire can be effective at reducing tree density and moderating fire behavior, particularly on landscapes with long histories of fire use and in areas of moderate burn severity (Hunter et al. 2011, Hunter et al 2014, Huffman et al. 2020). A recent study focused on Yosemite National Park demonstrated that managing natural ignitions increased landscape heterogeneity and likely improved resilience to drought (Boisramé et al. 2016). Other studies have also shown wildfires managed for resource benefits were mostly within the historical range of variability regarding burn severity by vegetation type and high-severity patch size (Collins and Stephens 2007; Meyer 2015; Meyer et al. 2010). Analysis of severity in a natural fire area of the Sierra Nevada in California found reasonable stability in the proportion of area burned among severity classes (unchanged, low, moderate, high) (Collins et al. 2009). General patterns of high severity, however, are still unknown within these two regions.

As the use of managed wildfire expands, it is important to conduct a retrospective analysis for mangers and policy makers to assess the temporal and spatial characteristics of managed fires. That is, we wish to better understand how managed fires differ from full suppression wildfires in terms of how, when and where these wildfires are burning. Given the importance of this fuel/restoration treatment tool it is also important to understand the social barriers and facilitating factors associated with implementing this tool and how all these factors have changed in since the 2009 *Policy Guidance*.

Objectives 1

To explore: a) what effect, if any, the *2009 Policy Guidance* had on the strategic response to wildland fires, and to what extent individual fires changed in terms of management duration and area burned and b) what effect, if any, the *2009 Policy Guidance* had on total area burned over the course of a fire season.

The methods used in this study are briefly summarized here, but our detailed methods and findings are thoroughly documented within the original study which was published in the International Journal of Wildland Fire (Young et al 2020). As a result, the wording used in that published paper is also used in this report to summarize this study but may vary from the wording used in the other component studies summarized in this report.

Materials and Methods

We categorised a historical fire population into fires managed with a suppression strategy to meet protection objectives, and fires managed with other strategies to meet resource objectives. We then analysed this population with a quasi-experimental, sharp regression discontinuity (SRD) design to determine what effect if any the *2009 Policy Guidance* had on the strategic response to wildland fires and associated objectives (Lee and Lemieux 2010; Calonico et al. 2014). As historical and current fire management policy suggests (Fire Executive Council 2009; Predictive Services 2014), we assume that suppression strategies are primarily used to meet protection objectives, whereas other strategies that allow fires to burn more naturally are primarily used to meet resource objectives. However, we acknowledge strategic responses are not restricted to incident objectives, nor are they mutually exclusive in their application over the course of a fire incident.

To arrive at our dataset for analyses, we compiled Situation report (SIT-209) from the Incident Status Summary (ICS-209) of 10,040 wildland fires in the western US from 2002 to 2016 inclusive of federal and state management. The SIT-209 reports guide the allocation of scarce fire management resources through an interagency process and are available via the FAMWEB Data Warehouse (Predictive Services 2014; SIT-209 2018). Data from 2015 were not available. Of the 10,040 fires, we excluded 670 determined to be constituents of a fire complex and 132 that were known duplicates, resulting in a final dataset of 9,238 fires. In total, we identified 7,084 large fires (≥40.5 ha) across the western US, which we grouped into the following six regions: California, Great Basin (Nevada and Utah), Inland Empire (Idaho and Montana), Northwest (Oregon and Washington), Rocky Mountains (Colorado and Wyoming) and Southwest (Arizona and New Mexico).

For the western US and each subregion, we performed a set of separate analyses. First, we summarized fire data by year (e.g. number and area burned) and size (i.e. <40.5 and ≥40.5 ha). Then we explored what effect, if any, the *2009 Policy Guidance* (as a policy treatment from 2009 to 2016) had on the strategic response to large (≥40.5 ha) wildland fires (Y_1), and to what extent large individual fires changed in terms of management duration (Y_2) and area burned (Y_3). In addition to the area burned by individual large fires, we also explored what effect, if any,

the *2009 Policy Guidance* had on total area burned (Y_4) within a fire year. We theorise each response (Y_i) to be defined by:

$$Y_i = P\gamma + F\varphi + W\alpha,\ i = 1,2,3,4,$$

where P represents an indicator variable for years after the *2009 Policy Guidance* (2009 to 2016) with the parameter estimate γ, F represents a vector of wildland fire variables with their corresponding parameter estimates φ, and W represents a vector of fire weather variables with their corresponding parameter estimates α. We modelled each response ($Y_{1,2,3,4}$) for fires that were managed predominantly with a full suppression strategy (noted herein as a 'suppression' strategy or fire, $Y_{i'Suppression'}$) and fires predominantly managed with strategies other than full suppression (noted herein as 'other' strategies or fire, $Y_{i'Other'}$). In our analyses, the implementation of the *2009 Policy Guidance* is the treatment effect, where fires from calendar year (CY) 2002 to CY 2008 represent the pre-treatment group and fires from CY 2009 to CY 2016 represent the post-treatment group.

Wildland fire (F)

For each individual fire, we collected variables from SIT-209 reports that are connected to the application of fire management strategies (see Table 1 in Young et al. 2020). The variables captured a fire's seasonality and potential to fulfill resource objectives (van Wagtendonk and Lutz 2007), and the fire's ignition source, accessibility and potential to cause harm to physical and human capital (Balch et al. 2017; Young et al. 2019). Variables also captured increasing trends in fire activity (Y_1), management duration (Y_2) and area burned ($Y_{3,4}$), which have been document in several studies throughout the western US (Westerling et al. 2006; Miller and Safford 2012; Westerling 2016; Singleton et al. 2019).

Fire weather (W)

We collected weather data from 779 Remote Automated Weather Stations (RAWS) across 137 Predictive Service Areas (PSAs) of the western US. These PSAs are continuous geographic areas with a homogeneous seasonal fire potential based on similar climates, topography and vegetation. Each fire was assigned weather data from the nearest RAWS station within the PSA of the fire's origin. Fires that shared data from the same RAWS station were defined as a 'fire cluster', which served as our spatial observational frames. We were able to verify the PSA and obtain the complementary weather data for 6658 large wildland fires (≥40.5 ha) across the 779 'fire clusters' (i.e. RAWS of weather origin) in the western US (California, 226; Great Basin, 92; Inland Empire, 154; Northwest, 144; Rocky Mountains 88; Southwest, 108). We ignored days with missing data when calculating observational weather metrics over the management duration of an individual fire (Y_2) and over periods with active fire management within a 'fire cluster' over the course of a 'fire season', i.e. 'fire year' (see Table 1 and 2 in Young et al. 2020).

Statistical methods

Using a quasi-experimental, SRD design (i.e. local linear, local quadratic and global parametric), we assessed 6658 large fires (≥40.5 ha) to investigate what effect, if any, the *2009 Policy Guidance* had on the application of fire management strategies (Y_i). To eliminate any potential bias from an improper specification of the functional form of the data-generating process, we

first fitted local univariate models (linear and quadratic) to assess the observed effects during the implementation of the *2009 Policy Guidance* (Lee and Lemieux 2010; Jacob et al. 2012). Then, to improve model precision, alleviate the potential for small-sample bias and more accurately determine what portion of the univariate effects could be attributed to the *2009 Policy Guidance*, we included fire and weather covariates in our local SRD models (Imbens and Lemieux 2008; Calonico et al. 2016). Finally, to improve model efficiency and assess the robustness of the policy's effects as assessed by local models, we examined the underlying distribution of the data-generating process and fitted the appropriate global model (Jacob et al. 2012; Wherry and Meyer 2016; Rudolph et al. 2018). Our global models assume a functional form that is consistent before and after the policy implementation (Lee and Lemieux 2010).

Although each subregion was analysed, we only discuss a subset of the results based on our ability to accurately assess 'other' fires. Within a local SRD framework, we determined the western US as a whole, as well as the subregions of the Inland Empire, and Southwest had robust samples for analyses across all four response variables ($Y_{i'Other'}$). This determination was based on power calculations (i.e. the probability of detecting a significant effect if present, $\beta_{\text{Power}} > 0.80$) (Imbens and Lemieux 2008; Cattaneo et al 2019). The Rocky Mountains are also discussed based on robust effects within our global SRD framework.

Observational units

When assessing how the *2009 Policy Guidance* affected a fire's management duration (Y_2) and area burned (Y_3), we used large individual 'suppression' and 'other' fires as observational units (see Table 2 in Young et al 2020). When assessing how the *2009 Policy Guidance* affected the application of fire management strategies over the course of a fire season (Y_1) and the total hectares burned (Y_4) by each fire classification, we used 'fire years' (see Table 1 in Young et al. 2020). Over the course of each 'fire season', if a wildland 'fire cluster' (see *Fire weather* above) had at least one fire, it resulted in a pair of 'fire year' observations, one for each fire type ('suppression' and 'other') where each observation contained the number of fires within the 'fire year'. Counts of zeros were most common in 'other' fire observations. The total number of 'fire years' in our dataset was equal to the total number of 'fire cluster' and 'fire season' combinations that contained at least one fire from 2002 to 2016. In total, we had 7500 'fire years' (3750 'suppression' and 3750 'other') with an average of 1.54 'suppression' fires per 'fire year' (range: 0 to 44 fires) and 0.23 'other' fires per 'fire year' (range: 0 to 11 fires).

Within the 'fire year' models, the isolated nature of 'other' fires across the western US combined with the derivation of the observational units resulted in zero inflated data for both the 'suppression' and 'other' fires. Though the presence of zero inflated data does not affect our local SRD design (Lee and Lemieux 2010; Jacob et al. 2012), our global techniques improve model precision by properly leveraging the source of zero inflation (Hu et al 2011).

Results and Discussion

Number and area burned (West wide)

Our investigation of 9,238 fires from 2002 to 2016, provides insight into changing wildland fire management in the western US, with evidence pointing towards the *2009 Policy Guidance* having a meaningful effect. When considering confounding variation that originated from concurrent fire and weather conditions (i.e., multivariate models), the contribution of the *2009 Policy Guidance* was estimated to be a 53 to 73% increase compared with the average in the western US from 2002 to 2008. Of an estimated 148 (i.e. 0.19 × 779) to 164 additional 'other' fires per year, we estimate that 62 to 86 were the result of the *2009 Policy Guidance* (Fig. 1). For comparison, our global SRD count model estimated a 27% increase in the number of fires being managed with 'other' strategies (see Table 4 in Young et al. 2020). When examining changes in management duration of 'other' fires due to the *2009 Policy Guidance*, our local linear model with a 6-year bandwidth estimated a 9-day increase. This equates to a 16% increase compared with 55 days, the average management duration of 'other' fires from 2002 to 2008. Similarly, our global count model estimated a 36% increase in management duration (see Table 5 in Young et al. 2020) and effect that was determined to be robust across space and time.

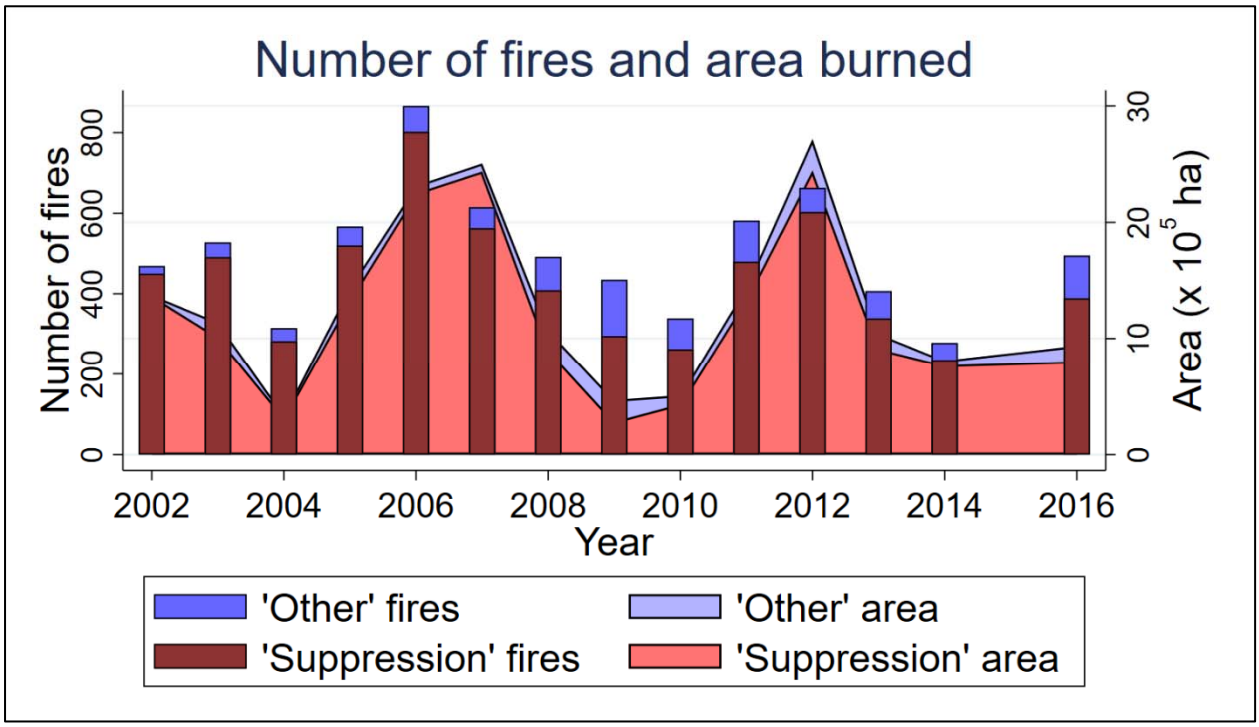

Figure 1. Number of large wildland fires (≥40.5 ha) and area burned (ha) by dominant strategy from 2002 to 2016 in the western US. The stacked bars represent the number of wildland fires per year (left *y* axis), where the red ribbons symbolise 'suppression' fires and the blue ribbons symbolise 'other' fires. The stacked area plots represent area burned by wildland fires per year (right *y* axis), where the red area symbolises 'suppression' fires and the blue area symbolises 'other' fires.

The total annual area burned by wildland fires varied greatly by dominant strategy type and follows the general oscillation of the number of fires (Fig. 1). The 'suppression' hectares fluctuated widely (Fig. 1), while total annual area burned by 'other' fires was relatively stable. 'Suppression' fires represent between 60% (2009 with 282,157 ha) and 99% (2002 with 1,368,951 ha) of total area burned, with an average of 89%. We found that 33% of small fires (<40.5 ha) and 9% of large fires (≥40.5 ha) were managed with 'other' strategies before 2009, (Fig. 1), which increased to 61 and 19% from 2009 to 2016. In 2008, California drove an increase in area burned by 'other' fires (102,737 ha), whereas the Inland Empire drove an increase in 2012 (Fig. 2) 236,779 ha). The Rocky Mountains have consistently contributed to area burned by 'other' fires since the *2009 Policy Guidance*, with a peak in 2013 (61,665 ha). Considerable area burned using 'other' strategies was also observed in the Southwest, particularly in 2003 (70,638 ha), 2009 (114,325 ha) and 2016 (74,511 ha).

Regional differences

There were however regional differences (Fig. 2). For example, the most notable increases in the management of large fires with 'other' strategies were in the Inland Empire, Rocky Mountains and Southwest regions, which managed a higher percentage of large fires with 'other' strategies after 2009 (24, 22 and 30% respectively) (Fig 2). California, however, continued the application of 'suppression' strategies on most large fires (≥40.5 ha), likely in part owing to a historic drought in this region from 2012 to 2016.

Other regional variations in fire metrics reflect recent and historic differences in fire management strategies. For example, though we found robust evidence that the *2009 Policy Guidance* has increased the number of 'other' fires in the Inland Empire and Rocky Mountains (Fig. 2), we only found limited evidence of an increase in total area burned by 'other' fires annually in the Inland Empire (Fig. 2), and modest evidence of an increase in area burned by 'other' fires individually and in total in the Rocky Mountains (Fig. 2). In the Southwest, however, we only found modest evidence of an increase in the number of large fires managed with 'other' strategies annually, along with modest evidence that 'other' fires burned a greater area in total within a 'fire year'. This was to be expected given the high number of large 'other' fires in the Southwest before the *2009 Policy Guidance* (Fig. 2), including the 2003 Dry Lakes Complex Fire (38,276 ha), the 2003 Boiler Fire (23,639 ha) and the 2005 Black Range Complex Fire (32,579 ha). Our only widespread result was the significant increase in the areas experienced 'other' fire(s) only over the course of a fire season.

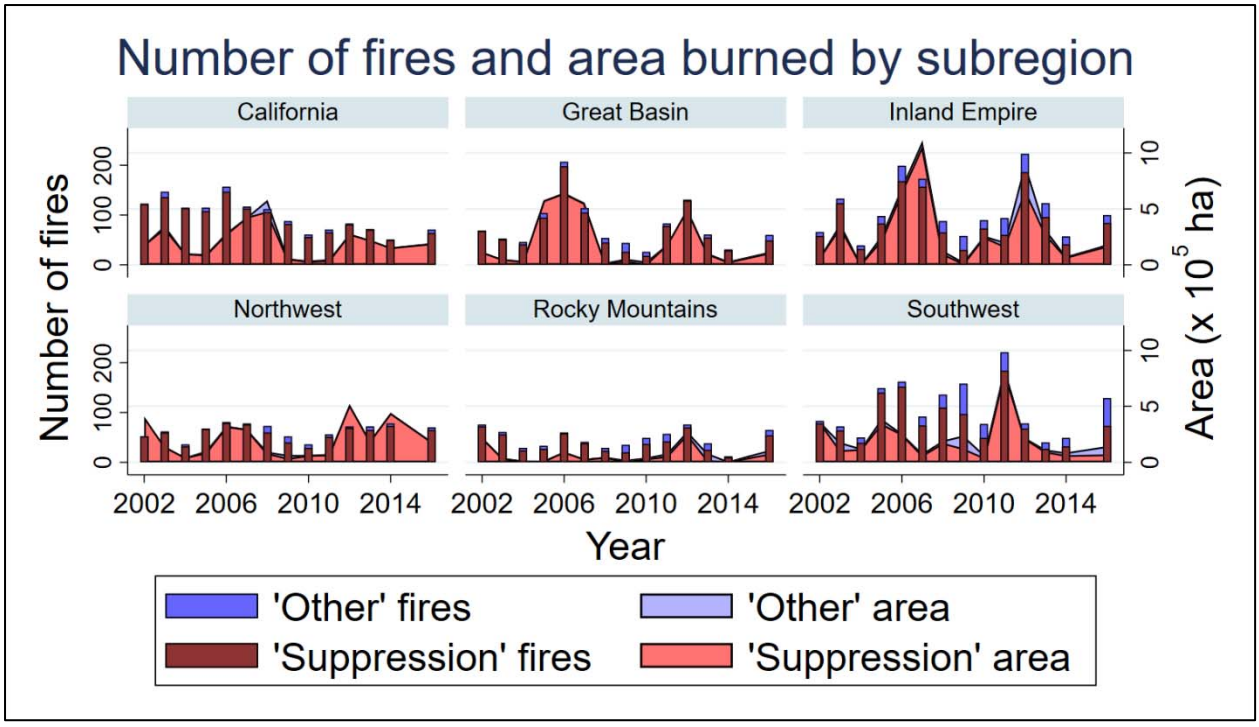

Figure 2. Number of large wildland fires (≥40.5 ha) and area burned (ha) by dominant strategy from 2002 to 2016 for each subregion. The stacked bars represent the number of wildland fires per year (left *y* axis), where the red ribbons symbolise 'suppression' fires and the blue ribbons symbolise 'other' fires. The stacked area plots represent area burned by wildland fires per year (right *y* axis), where the red area symbolises 'suppression' fires and the blue area symbolises 'other' fires.

Fire Seasonality

Seasonal 'suppression' fire activity in the western US peaked in July (Fig. 3, day of year ~182 to 212), whereas the average 'other' fire began in early August and continued well into September (day of year ~227 to 273). The mean management duration for 'suppression' fires was 11 days, whereas the mean management duration for 'other' fires was 52 days, with 2011 and 2012 having a mean control date as late as early October (Fig. 3). Moreover, the mean discovery date for 'other' fires was commonly after the mean control date for 'suppression' fires (e.g. 2002, 2008, 2009, 2011 and 2012). In other words, the average seasonal occurrence of 'other' fires ensued after many of the 'suppression' fires had been controlled. Like the western US overall, 'suppression' fires in each region had shorter management durations and 'other' fires had a mean discovery date that was later in the year.

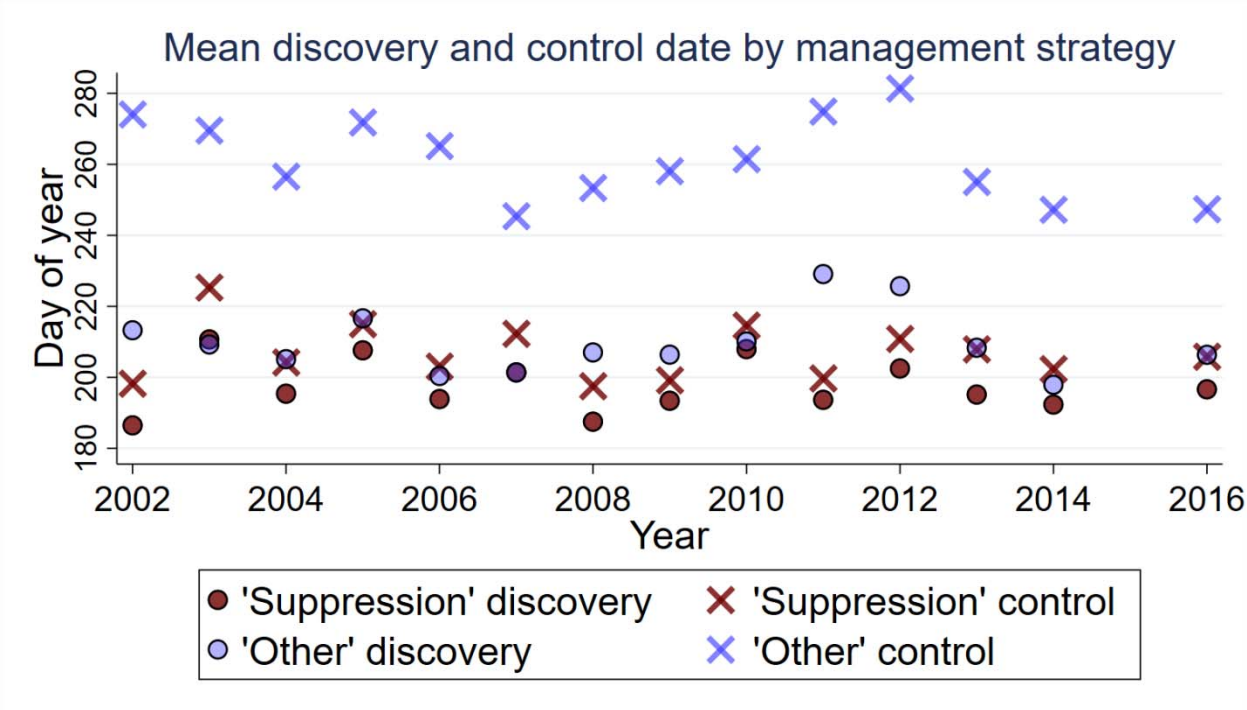

Figure 3. Mean discovery and control dates for large 'suppression' and 'other' fires (≥40.5 ha) in the western US. For non-leap years: Day 180 = 29 June; Day 220 = 8 August; Day 260 = 17 September.

Effects of the 2009 Policy Guidance – SRD results

Though our analyses provide evidence that the *2009 Policy Guidance* and other advances in fire management (e.g. WFDSS) have lifted some barriers related to national policy directives and agency culture, other barriers still exist. These include local policies (e.g. restrictive forest plans), cultural barriers (e.g., risk aversion of planning team), constraints related to political boundaries (e.g., transmission of fire risk), organisational capacity to manage fires for an extended period of time, and public perceptions of wildland fires in an expanding WUI (Kneeshaw et al. 2004; Doane et al. 2006; Meyer et al. 2015; Ager et al. 2017b; Kelley 2017). Arguably, the most important barrier remains the high accumulation, and the continuity of fuels across the landscape (Keane et al. 2002; Calkin et al 2015). Though the need to overcome these barriers is great, the application of wildland fires to meet restoration goals should be exercised with caution in nascent fire programs to build a solid foundation for the future. That is, a modest increase in area burned by a significant addition of small 'other' fires when circumstances allow is an advisable approach towards increasing the heterogeneity of landscape fuel conditions (Hunter et al. 2014). This gradual strategy allows local personnel to gain experience using wildland fires to meet resources objectives (Wilson et al, 2011) while building social acceptance. Satisfying these prerequisites is needed to successfully meet resource objectives with the management of large wildland or prescribed fires (~20 000 ha) (Hunter et al. 2014). As some of the aforementioned factors are addressed, we expect to see an increase in the size of prescribed fires and wildland fires being managed with 'other' strategies.

Weather and seasonality

Our results also suggest that weather conditions are key determinants of fire management decisions and the ability to restore fire as a natural process, similarly to a previous study in the Southwest (Young et al. 2019). Whereas weather conditions predictably dictate the application of 'suppression' *v*. 'other' strategies based on expected fire behaviour (see Table 8 in Young et al. 2020), the effects detected in our 'individual fire' models are more nuanced, based on the relative ability to carry out a fire manager's desire to contain a fire and what natural burning conditions would dictate under varying conditions. For example, an average 'suppression' or 'other' fire with high WINDS was managed for a relatively shorter time compared with an average fire with docile WINDS (see Table 8 in Young et al. 2020) –7.06 and –5.92% duration per unit increase in WIND), capturing more aggressive firefighting tactics to minimise potential for large high-severity fires when high WINDS prevail (Lydersen et al. 2017). At the same time, despite the desire to limit a fire's duration, the average 'suppression' fire with high WINDS burns a greater area (+3.69% area per unit increase in WIND) as the fire line intensity increases and this overpowers the desire to limit the fire's duration (Lydersen et al. 2017).

Other effects detected in our models offer insight into weather conditions conducive to 'other' strategy use. For example, increasing PRECIPITATION on an average 'other' fire was associated with longer management duration and greater area burned when there were high WINDS to help carry the fire (+34.07% area per unit increase in PRECIPITATION). Surprisingly, under docile WINDS, the average 'suppression' fire increased in size as PRECIPITATION increased (see Table 8 in Young et al. 2020), potentially as other fires or objectives took precedence. Similarly, a 'fire year' with docile WINDS during active fire management experienced a larger number of hectares burned when there was additional PRECIPITATION. This effect is true regardless of the predominant management strategy (see Table 7 in Young et al. 2020), suggesting a greater willingness to allow fires to play a natural role during docile weather conditions that support lower burn intensity and minimise the probability of uncontrollable fire spread. Similar conclusions have been drawn in previous studies in the Southwest (Huffman et al. 2017). These complex weather effects make controlling for confounding variation essential when performing a policy analysis of a highly stochastic process like wildland fire, especially when considering seasonal droughts, the El Niño–Southern Oscillation cycle and the effects of climate change (Swetnam 1990; Westerling et al. 2006; Jolly et al. 2015; Westerling 2016).

Just as our weather variable results revealed that burning conditions play a deciding role in fire management, our seasonality analysis revealed a similar distinct pattern. Compared with 'other' fires, the average 'suppression' fire began earlier in the year and had a shorter duration, likely resulting from the impending seasonal drought during peak fire season that fosters greater fire growth and adverse fire effects (Williams et al. 2005), especially in forests with high fuel loads (Keane et al. 2002). Conversely, 'other' fires commonly ignited after the control of most 'suppression' fires and continued to burn well into fall (autumn) or after the advent of the North American monsoon. Under these conditions, 'other' fires are more likely to be lower intensity and thus reduce fuels with minimal risk of escaping control lines as cooler, wetter weather patterns set in (Fites-Kaufman et al. 2006; Knapp et al. 2009). Concentrating 'other' strategy use during narrow weather windows in fall shoulder seasons limits their size, which in

part explains the limited increase in area burned by individual 'other' fires. In order to catalyse an expansion of area burned by 'other' strategies into broader shoulder seasons, including the spring, land managers will first have to reduce fuel loads with an increasing pattern of prescribed burning and mechanical treatments, followed by larger moderate-intensity wildland fires managed for resource objectives with strategies other than full suppression. Overall, to expand the use of 'other' strategies to maintain fuels reduction treatments, there will have to be a willingness to accept higher risk including that associated with expanding the weather window. This is consistent with other suggested changes in management that are needed to create more resilient systems that have not yet been achieved (Calkin et al. 2015; North et al. 2015).

Conclusions (Key Findings) and Management Implications

West wide patterns:

- When considering confounding variation that originated from concurrent fire and weather conditions, the contribution of the *2009 Policy Guidance* was estimated to be a 27 to 73% increase compared with the average in the western US from 2002 to 2008.
- A greater portion of wildfires are being manage with 'other' strategies after 2009.

Regional Differences:

- The most notable regional increases in the management of large fires with 'other' strategies were in the Inland Empire, Rocky Mountains and Southwest regions, which managed a higher percentage of large fires with 'other' strategies after 2009 (24, 22 and 30% respectively compared to 19% in the western US).
- Although we found a general increase in the number of wildfires managed with 'other' strategies after 2009 that did not necessarily translate to greater area burned.

Weather and Seasonality

- In general, wildfires managed with 'other' strategies are longer in duration (52 days compared to 11 days for suppression fires), burned later in the year (the average seasonal occurrence of 'other' fires ensued after many of the 'suppression' fires had been controlled), and occurred during more docile weather conditions.
- Surprisingly, under docile wind conditions, the average 'suppression' fire increased in size as precipitation increased, suggesting the application of 'other' strategies

These findings suggest that the 2009 Policy Guidance has significantly increased the use of other management strategies, but this has not necessarily translated into a large increase in area treated. Overall, this suggests a greater willingness to allow fires to play a natural role during docile weather conditions that support lower burn severity and minimize the probability of uncontrollable fire spread.

Objectives 2

This second objective of this project focused on assessing the effects of fires managed for ecological/resource benefit and full-suppression fires by investigating:

a. whether spatial patterns of high-severity patches differed by management strategy, and
b. whether spatial patterns were related to fire size and percent high-severity fire

Materials and Methods

We examined high-severity spatial patterns within large fires using satellite-derived burn severity data from 735 fires that burned from 1984-2017 in Arizona and New Mexico, USA. This was done by mapping burn severity for all large fires (> 404 ha) in Arizona and New Mexico from 1984-2017 across all ownerships of forested land (Fig. 4). For each fire, we derived Landsat-based severity data (RdNBR; Miller and Thode 2007) by implementing Parks et al. (2018b) novel burn severity mapping methodology within the Google Earth Engine (GEE) platform. We obtained fire perimeter shapefile data for Arizona and New Mexico from the Monitoring Trends in Burn Severity (MTBS) project and input these data into Parks et al. (2018b) open-source code within GEE (Eidenshrink et al. 2007; Voss et al. 2018). We selected the 'RdNBR with offset' calculation and set the scene-stacking date range from April to June (*sensu* Parks et al. 2018b). We chose the RdNBR index over other burn severity indices (e.g., dNBR or RBR) to account for change relative to pre-fire vegetation cover and to facilitate comparisons among multiple fires (Miller and Thode 2007). The offset calculation is applied to RdNBR images to account for potential phenological differences in pre- and post-fire scenes. For each fire, the offset is determined by averaging dNBR values within a 180 m ring outside the fire perimeter and subtracting this value from the dNBR raster (Parks et al. 2018b).

We used the ERU layer to map RdNBR pixels that burned in forest or woodland vegetation types (Whalberg et al. 2014) and retained all fires that burned ≥40% of its area within forests and woodlands for analysis. Then, for each fire, we classified continuous RdNBR data into a single binary class representing high-severity by applying a field-validated threshold value. We used regression analysis to model the relationship between 1,283 field measurements of burn severity (composite burn index; CBI) and their corresponding RdNBR values (Fig. 2). From this model, we calculated a high-severity threshold equivalent to a CBI ≥ 2.25 (RdNBR ≥ 687). Field-measured CBI values ≥ 2.25 represent ≥ 95% basal area mortality (Rivera-Huerta et al. 2016; Lyderson et al. 2017). The CBI plot field measurements were taken in fires that burned in the Grand Canyon National Park, Coconino, and Gila National Forests (Gdula and Brannfors, 2014).

Fires were also classified based on management strategy and categorized as either "suppression fire" or "managed fire". We define managed fires as prescribed burns, Wildland Fire Use (WFU), or resource objective fires. We used the MTBS database to classify fires from 1984-2008 then used Young et al. (2019) suppression containment model along with Inciweb reports to identify the dominant management strategy from 2009 to 2017 (inciweb.nwcg.gov). MTBS classifications were not used after 2008 due to the release of the Guidance for Implementation of Federal Wildland Fire Management Policy in 2009, which effectively removed the classification of fires as Wildland Fire Use (US DOI/USDA 2009). In cases where we

were unable to identify a fire's dominant management strategy, they were excluded from the study (n=83).

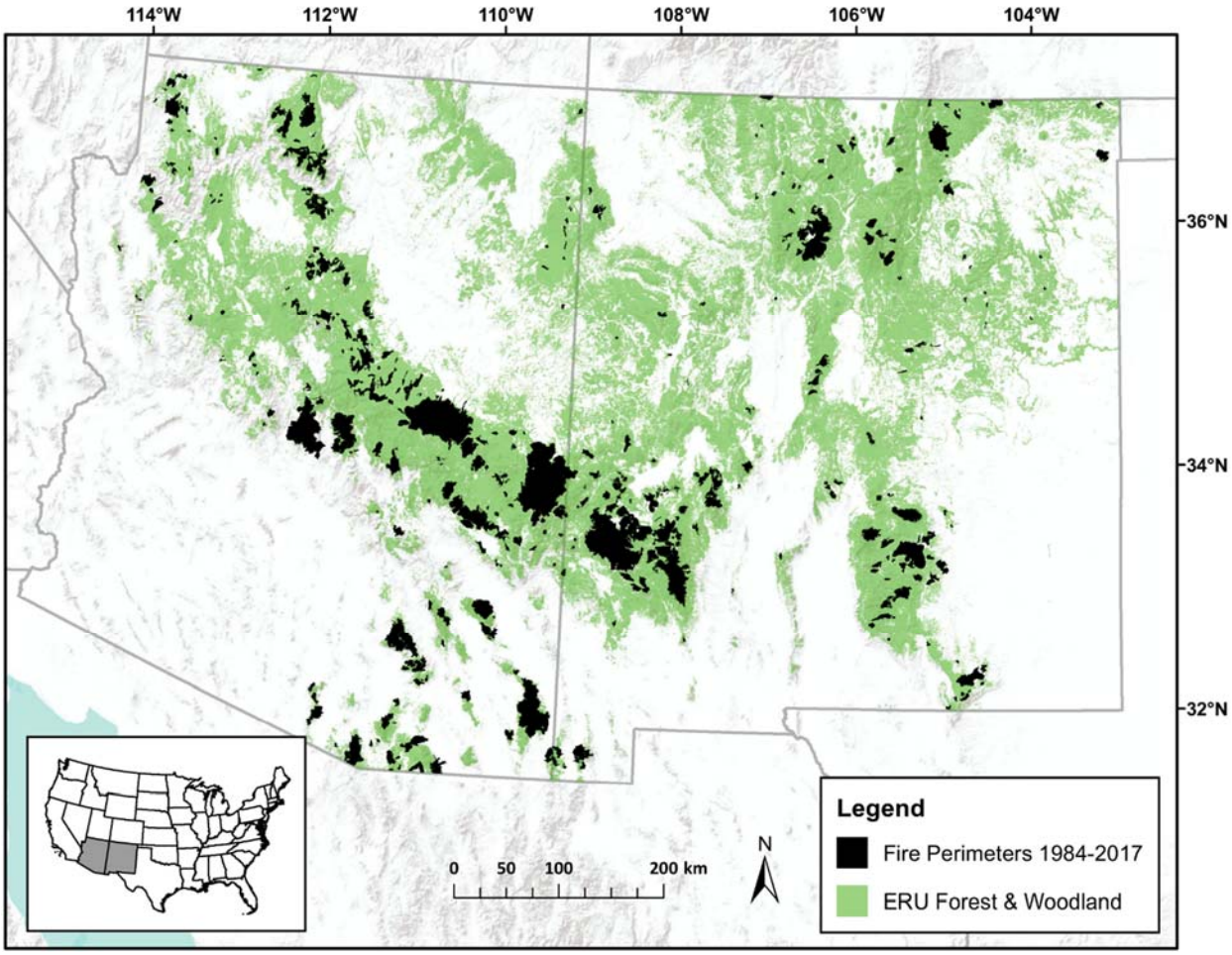

Fig 4. Map of the study region in Arizona and New Mexico, USA showing location of the 735 large fires (> 404 ha) in this study that burned between 1984-2017. Fires were separated by management type (suppression fires n=493; managed fires n=242) and sampled to analyze spatial patterns of high-severity fire. Green shading represents the distribution of forests and woodlands based on the Ecological Response Unit Framework (Whalberg et al. 2014).

Metrics that parsed out the most variability were: (1) area-weighted mean radius of gyration (GYRATE_AM), (2) area-weighted mean perimeter area ratio (PARA_AM), (3) percentage like adjacencies (PLADJ), and (4) total core area (TCA; Table 1; McGarigal and Marks 1995). In addition to these four metrics identified from the PCA and cluster analysis, we selected two other metrics for evaluation: Class area (CA) and the stand-replacing decay coefficient (SDC; Table 1). CA is a commonly reported 'basic' metric that describes the total high-severity area within individual fire perimeters and was selected to draw comparisons to recent burn severity analyses (Dillon et al. 2011; Harvey et al. 2016; Steel et al 2018). We also included the novel SDC metric because it utilizes an ecological-based approach to quantify the relationship between percent high-severity and the distance to patch edge (Collins et al. 2017; Stevens et al.

2017). The SDC metric is unique in that it encompasses multiple patch characteristic categories including patch size, shape, and core area. In total, we used six metrics to quantify the spatial pattern of high-severity fire in the southwestern US.

Statistical Analysis

To address objectives one and two, we investigated differences in spatial pattern of high-severity burn patches as a function of fire management strategy (managed vs suppression fires), fire size, and percent high-severity. To test for significant differences in spatial pattern metrics of high-severity burn patches by management strategy, we used the nonparametric one-way Kruskal-Wallis ANOVA test ($\alpha = 0.05$; Hollander and Wolfe 1973). To test if fire size and percent high-severity were significant predictors of each spatial pattern metric, we used simple linear regression and beta regression models ($\alpha = 0.05$). Specifically, we used ordinary least squares (OLS) models for CA, GYRATE_AM, TCA, PARA_AM, SDC data and beta regression models for PLADJ data since these models are designed to accommodate common issues with rate or proportion data such as heteroskedasticity and asymmetrical distributions (Cribari-Neto and Zeileis 2010; Schmid et al. 2013).

Results and Discussion

Differences between managed and suppression fires

All six spatial pattern metrics of stand-replacing fire differed significantly between management strategies in the study area (Arizona and New Mexico) (Fig 5). High-severity burn patches in suppression fires had greater area, reach, aggregation, total core area, were simpler in shape, and decayed slower than patches in managed fires. These results are likely a function of burning and weather conditions. Suppression fires generally coincide with extreme weather events which drive fire growth, severity, and subsequently, more homogeneous spatial patterns (Collins 2014). Comparatively, managed fires are allowed to burn under mild or average weather conditions thereby inhibiting fire spread, intensity, and the potential for large patches (Young et al. 2019). Significant differences between fire management strategies also suggest that spatial patterns of high-severity burn patches in suppression fires are outside the historical range of variability (HRV) for some forest types. Based on tree-ring reconstructions, the largest stand-replacing patch sizes ranged from 200 to 1,000 ha in southwestern mixed conifer-aspen and spruce-fir forests (Margolis et al. 2011; O'Conner et al. 2014) and were typically less than 1 ha (Pearson 1923) but up to 60 ha in ponderosa pine forests (Iniguez et al. 2009). Based on our results, the median and maximum area-weighted mean patch sizes in managed fires was within the HRV for both mixed conifer-aspen and spruce-fir and dry conifer forests (i.e., 2.3 ha and 581 ha respectively). Within suppression fires, the median area-weighted mean patch size (10 ha) was close to historical ranges in dry forest types, but the maximum patch size (7,561 ha) was seven times larger than the HRV for upper elevation forests and at least 126 times larger than the HRV for dry forests. Due to inherent difficulties of reconstructing incomplete extant data, it is unclear whether other spatial metrics such as patch aggregation or shape are outside HRV. However, it is evident that contemporary fires under a suppression management strategy have resulted in significant departures from historical spatial patterns of high-intensity fires, particularly related to patch size in dry conifer systems. This finding is concerning given that dry

coniferous forests are not adapted to large and intense fire, and these vast and contiguous severely burned patches could potentially be at risk for fire-facilitated vegetation conversion (Coop et al. 2020).

While spatial patterns appear to be changing in suppression fires, high-severity patch sizes in managed fires are closer to historical ranges and thus, are better aligned to function as they did historically. Although high-severity fire can adversely impact conifer stands, the heterogeneity of severity classes within reintroduced fires is an important component towards increasing forest resilience. Managed fire that incorporates fine-grained patches of high-severity, along with a mosaic of unchanged, low, and moderate severity classes creates wildlife habitat diversity, promotes post-fire regeneration, and moves forests towards a more resilient state (Roberts et al. 2015; Huffman et al. 2017; Collins et al. 2018). In particular, moderate severity is effective in meeting structural and hazardous fuel restoration targets in ponderosa pine stands (Huffman et al. 2017) and is important for decreasing risk of future crown fire and restoring natural fire regimes (Collins et al. 2018; Hunter et al. 2011). Managed fires that burn more actively are likely to have a more complex burn mosaic and high-severity fire effects are often a necessary in order to increase the representation of moderate effects on the landscape. Thus, current high-severity patch sizes in dry forests could be ecologically beneficial in order to achieve a matrix of severity classes and achieve greater landscape heterogeneity of fuel conditions.

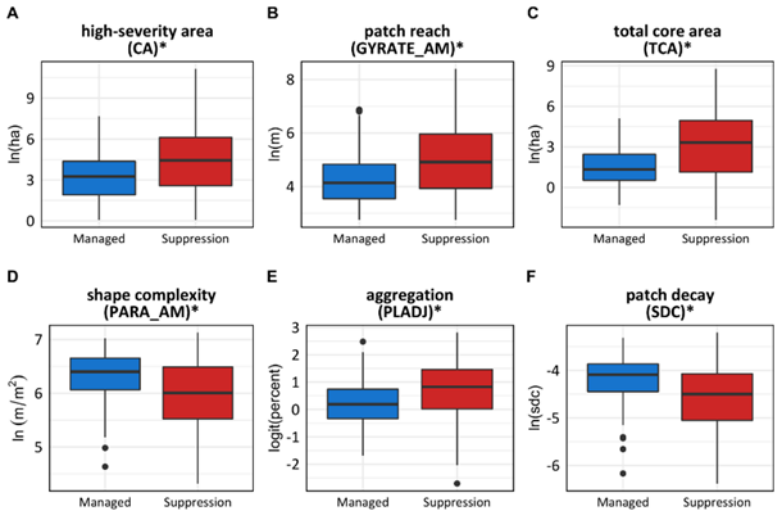

Fig. 5. Boxplots showing spatial pattern metrics of high-severity burn patches as a function of fire management strategy. High-severity burn patches in suppression fires (red) have greater (A) area, (B) extent, (C) total core area, (D) are simpler in shape, (E) have greater aggregation, and (F) decayed slower than high-severity patches in managed fires (blue). Comparisons were made using non-parametric one-way Kruskal-Wallis ANOVA test. Graphs are in transformed units for interpretability. Asterisk (*) indicates significant differences ($\alpha = 0.05$; $P \leq 0.0001$)

Relationships between high severity burn patches and percent high severity

From 1984-2017, the 735 large fires observed in this study burned a total of 2,661,819 ha in forests and woodland systems with 17% burning at high severity. Fire size was a significant predictor of all metrics ($P \leq 0.005$; Fig. 6) and was most strongly correlated with class area (CA) for both managed and suppression fires ($R^2 = 0.44$ and $R^2 = 0.16$, respectively; Fig. 6a). Percent high-severity fire was also a significant predictor of all six spatial pattern metrics and was a stronger predictor than fire size based on higher correlations values ($P < 0.0001$; Fig. 7). In general, percent high-severity in suppression models had stronger correlations with spatial pattern metrics compared to managed fire models (Fig. 7). Percent high-severity had the highest correlations with patch reach (GYRATE_AM) in suppression fires and class area (CA) in managed fires.

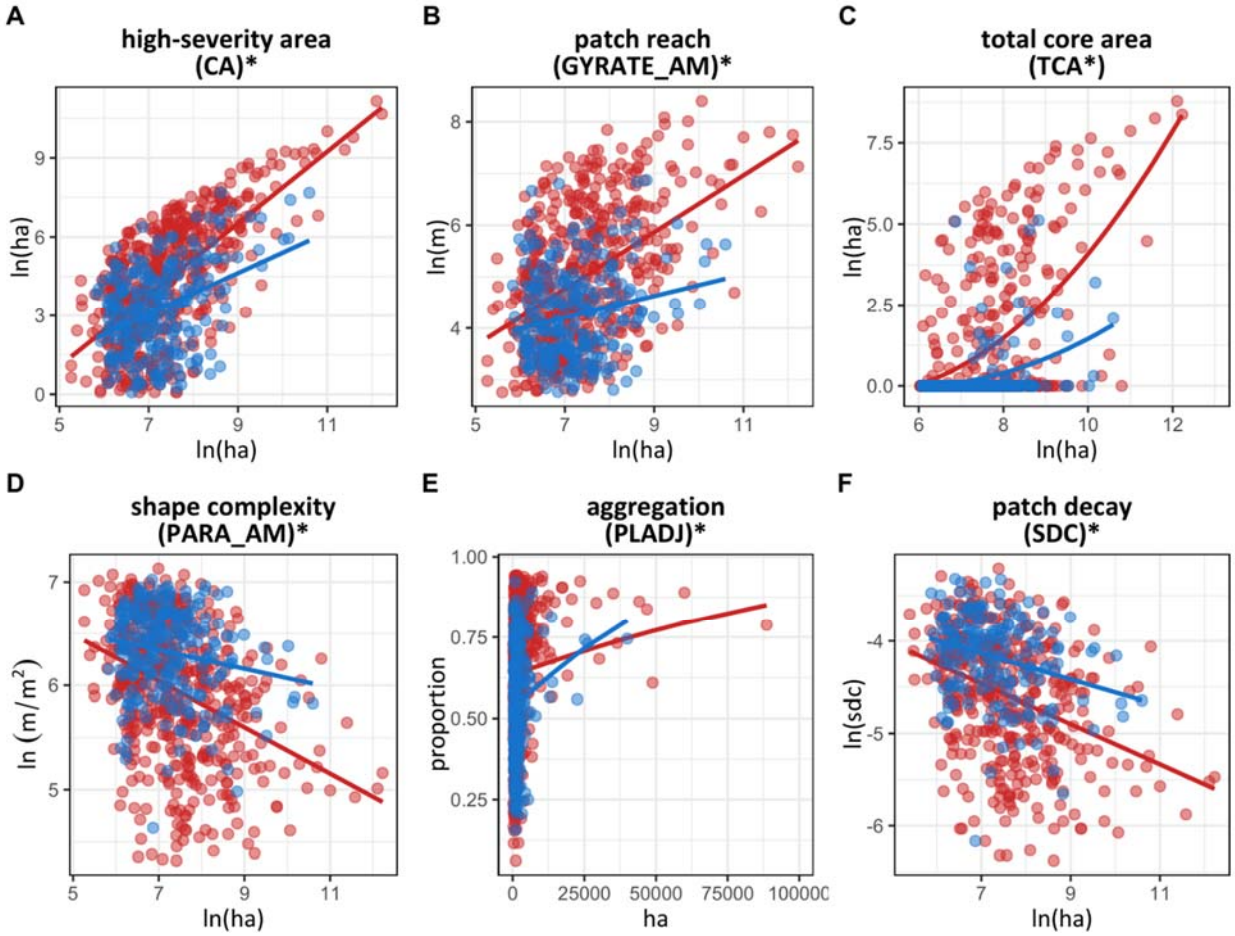

Fig. 6. Relationship between fire size (burned area) and high-severity spatial pattern metrics stratified by suppression fires (red) and managed fires (blue). As fire size increased, (A) area burned severely increased, (B) patch extent increased, (C) total core area increased, (D) patch complexity decreased, (E) aggregation increased, and (F) decayed slower in both fire types. Asterisk (*) indicates significant relationship ($P \leq 0.005$) for both managed and suppression fires.

As fire size and percent high-severity fire increased, spatial patterns of high-severity burn patches were more contiguous, aggregated, simpler in shape, and decayed faster regardless of management strategy. Our results are consistent with relationships found between fire size and

spatial pattern metrics of high-severity fire in the northern Cascade Range, northern Rocky Mountains, and California conifer forests (Cansler and McKenzie 2014; Harvey et al. 2016; Stevens et al. 2017). The consistency in results across the western US suggests that as fires become larger, they will generate more homogenous high-severity patch characteristics, regardless of region and other potential driving factors such as climate or topography.

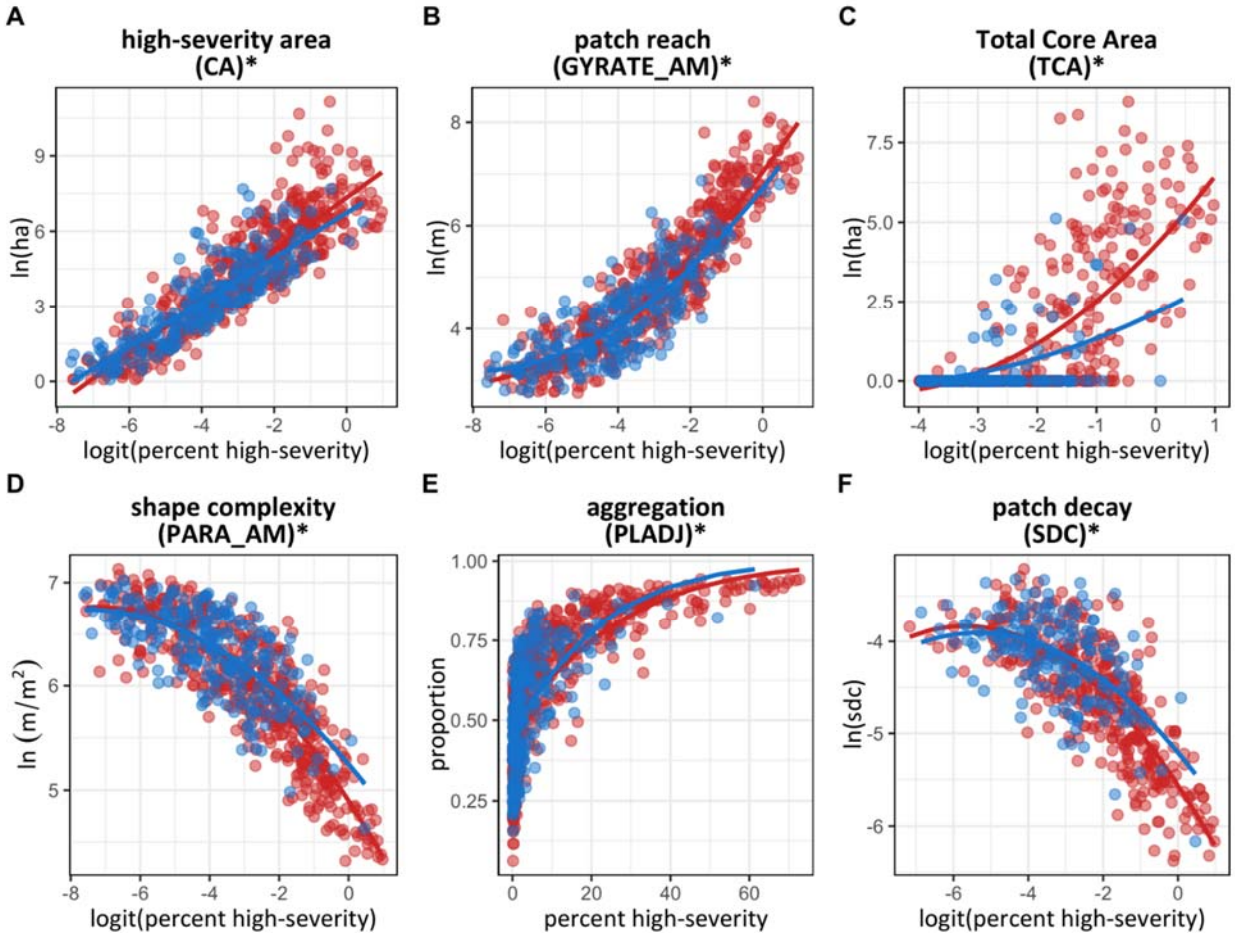

Fig. 7. Relationship between percent high-severity fire and spatial pattern metrics of high-severity burn patches stratified by suppression fires (red) and managed fires (blue). As the percent of high-severity fire increased, the spatial pattern of burn patches showed: (A) greater area, (B) greater extent, (C) greater core area, (D) simpler shapes, (E) greater aggregation, and (F) slower decay in both fire types. Asterisk (*) indicates significant relationship ($P \leq 0.0001$) for both managed and suppression fires.

Compared to the linear relationships with fire size, spatial pattern metrics generally exhibited strong, quadratic relationships with percent high-severity fire. These nonlinear responses were expected based on previous work showing the relationship between landscape processes and observed patterns (Gardner et al. 1987; Turner et al. 1989). As demonstrated in neutral landscape models, the connectivity of patches changes as a function of the proportion of a given class: As proportion increases, a network of clustering patches will develop and undergo a phase transition (i.e., nonlinear response) to a single spanning cluster once a critical threshold is reached (Gardner et al 1987; Gustafson and Parker 1992; Harvey et al. 2016; Villard et al. 2014).

In our analysis, patch shape (PARA_AM), aggregation (PLADJ), and decay (SDC) exhibited nonlinear behavior with increases in percent high-severity, suggesting that numerous smaller patches eventually coalesced into fewer but larger homogenous patches after reaching a critical threshold (Gustafson and Parker. 1992). Similarly, a study in the Northern Rocky Mountains documented sharp increases in patch size and core area when percent high-severity exceeded a threshold of 35% (Harvey et al. 2016). Although quantifying critical thresholds was beyond the scope of this study, identifying these values for burn severity patterns in the Southwest have important implications for management where percent of high-severity fire might serve as an effective metric to better predict stand-replacing effects or trigger alternative suppression or management actions. More research is needed in assessing critical threshold values for spatial patterns of high-severity fire; however, current research offers insight into predicting patterns of high-severity fire based on climate data. Mueller et al. (2020) have modeled the relationship between average maximum monthly Vapor Pressure Deficit (VPD) and the probability of surpassing a certain percent high-severity fire threshold in the Southwest. Thus, for a given VPD value, it is possible to estimate the probability of percent high-severity fire and high-severity patch characteristics using Mueller et al. (2020) model predictions and graphs generated in this study.

Conclusions (Key Findings) and Management Implications

- From 1984-2017, the 735 large fires observed in this study burned 2,661,819 ha in forests and woodland systems with 17% burning high severity.
- High-severity burn patches in suppression fires had greater area, reach, aggregation, total core area, were simpler in shape, and decayed slower than patches in managed fires.
- High-severity patch sizes in managed fires are closer to historical ranges and thus, are better aligned to function as they did historically.
- Percent high-severity fire was also a significant predictor of all six spatial pattern metrics and was a stronger predictor than fire size based on higher correlations values.
- As fire size and percent high-severity fire increased, spatial patterns of high-severity burn patches were more contiguous, aggregated, simpler in shape, and decayed faster regardless of management strategy, leading to greater homogenization of the forest landscape.

Identifying critical values for burn severity patterns in the Southwest have important implications for management where percent of high-severity fire might serve as an effective metric to better predict stand-replacing effects or trigger alternative suppression or management actions. Although high-severity fire can adversely affect conifer stands, the heterogeneity of severity classes within reintroduced fires is an important component towards increasing forest resilience and diversity. Managed fire that incorporates fine-grained patches of high-severity, along with a mosaic of unchanged, low, and moderate severity classes creates wildlife habitat diversity, promotes post-fire regeneration, and moves forest landscapes towards a more resilient state.

Objective 3

The third objective was to identify differences between wildfires managed with full suppression and other strategies in proximity to wilderness, proximity to WUI, multijurisdictional management, and burn severity across (a) suppression strategy (b) space (regional) and time (before and after 2009).

Methods

To arrive at the final wildfire database for our analysis, we used the Monitoring Trends in Burn Severity (MTBS) database. This product maps the extent, size, and severity of all large fires greater than 1,000 acres (404 ha) in the west and 500 acres (202 ha) in the east over the entire United States (MTBS.gov). We extracted MTBS fires in our study area, including Arizona and New Mexico (Southwest), and California from 2002 to 2016. We then used the Young et al. (2020) dataset to enrich the MTBS dataset. The Young et al. dataset was compiled using Incident Status Summary (SIT-209) from FAMWEB Data Warehouse to determine the dominant fire management strategy for 10,040 fires within the western United States between 2002 and 2016. Due to a lack of a common key between the Young dataset and MTBS fire perimeters, a manual procedure was used to match fires with similar attributes, including state, year, name, date, and size. A total of 1,109 MTBS burn perimeters were matching the Young et al. dataset. We extracted the management strategy for these fires and added them to our MTBS-based dataset. For fires only found in the MTBS database, we used MTBS to identify the fire management strategy when that was available and deleted fires with an unknown strategy. We also deleted the fires with more than 50% of the area outside the study area. Following these procedures, we were able to attain burn perimeters, severity, and management strategy for 1,434 fires ranging from 405 to 228,107 ha in size.

For each wildfire, we calculated the proximity to WUI and wilderness areas as well as the percent of high severity and the number of agencies within the fire perimeter. Wildfires that burned within a designated wilderness or WUI area where assigned a distance of zero while the closest distance between the fire perimeter and the wilderness/WUI area was determined for all other fires. We calculated proximity to wilderness using a spatial dataset of all national wilderness designated areas. Wildland Urban Interface (WUI) areas were determined using the SILVIS Lab dataset. The SILVIS lab used a spatial analysis between National Land Cover Data and US Census housing data to delineate areas of WUI in two categories: intermix and interface (Stewart el al. 2007). For our purposes, we merged both intermix and interface areas for the year 2010 to represent a collective WUI area.

Surface Management Agency (SMA) polygon data were acquired from the National National Geospatial Data Asset and used it to asses the number of jurisdictions included within each fire. This dataset covers the continental United States and depicts agency surface land jurisdiction for a particular area. The spatial data contained within the SMA layer are a culmination of data housed at both federal and local government levels. Each agency classification in the SMA layer was dissolved to form 11 different categories: 7 federal agencies, an “other federal” category, state, local, and private/unknown. Percent high severity for each fire was based on a Singleton et al. (2021) fire severity dataset. Singleton calculated RdNBR for the MTBS perimeters by

implementing Parks et al. (2018b) novel burn severity mapping methodology within the Google Earth Engine (GEE) platform where high severity classes was defined as areas with RdNBR values greater than 687.

To examine proximity to wilderness, proximity to WUI and the percent high severity fire, we used an Empirical Cumulative Distribution Function (ECDF), which is the distribution function built from the empirical measure of a sample or population. Using ECDF as a basis for analysis, the sample median and interquartile range were compared between strategy (suppression vs. other), regional (SW vs. CA), and time (pre- vs post-2009), while accounting for non-equal variance between comparative samples using a Huber–White standard error. To examine multijurisdictional collaboration, the number of fire management agencies for each fire was determined using SMA spatial overlays. This data was examined with a discrete distribution function (DDF), and populations were compared using a Poisson model with mixed effects and Huber–White standard errors to account for a non-equal variance between comparative samples.

Results and Discussion

Strategy Differences

Over the last three decades the amount of area burned in the western United States has significantly increased (Dillon et al. 2011), a pattern that is likely to continue as the climate warms and dries. Given that many of these wildfires threaten human communities, populations within the western U.S. will need to learn to live with wildfires. To this end, our results clearly show that that not all wildfires are the same; managed and full suppression wildfires are distinctly different in terms of where and how they burn. Strategies to manage wildfires for resource benefits are used in remote wilderness areas further from WUI, usually involve a single agency, and tend to burn with less high intensity (Fig 8). The lower severity affects associated with managed wildfires is likely because these fires tend to occur later in the fire season and under milder weather conditions (Young et al. 2020). Our results are in line with prior research that show managed wildfires are commonly within the historical range of variability regarding burn severity (Collins and Stephens 2007; Meyer 2015; Meyer et al. 2015). Although high severity wildfire is a natural part of some forest types, forests where managed wildfire are being applied in these two regions are adapted to frequent, low-severity fire regimes. The reduction in both tree density and accumulated fuels associated with most managed wildfires can therefore be considered beneficial in terms of healthy forests and future fire behavior (Hunter et al. 2011). Nonetheless managers may need to allow for increased fire severity in managed wildfires in the future to meet land management goals (Huffman et al. 2020).

The practice of using fire to reduce fuels has been well established since the introduction of prescribed fire in the 1930s (Ryan et al. 2013). Nonetheless, the pace of prescribed fire failed to keep pace with fuels reduction needs (Kolden 2019) prompting the increased flexibility of using wildfire in wilderness areas in the 1960s and 70s as part of the Prescribed Natural Fire (PNF) program (Hunter et al. 2014, Ryan et al. 2013). This explains our findings that most managed wildfires occur within or close to wilderness areas, and makes sense given that mechanical

treatments are prohibited within wilderness areas. The PNF program was followed by increased flexibility on national forest in the 1990s (Federal Wildland Fire Policy 1995), making managed wildfire a key supplemental option to reduce tree densities and accumulated fuels. Still, the close proximity of managed wildfires to wilderness areas and the greater distance to WUI, is likely related to risk aversion by management agencies. This is consistent with prior research that revealed wildfires with an increased number of housing at risk, commonly receive an increased allocation of fire suppression resources (Wibbenmeyer et al. 2013, Young et al 2019). In some instances, the increased allocation is driven by a potential liability and damage to homes (Young et al. 2019), particularly those of high value (Bayham and Yoder 2020), while in other instances it is driven by an inflated sense of risk despite the likelihood of fire damage being low (Wibbenmeyer et al. 2013). Our findings support a continued aversion to managed wildfire in close proximity to WUI in favor of wilderness areas. To be effective at protecting WUI and other values at risk from uncharacteristic, high-severity wildfires (Ager et al 2021), an improved application of modern fire analytics is needed (e.g., Calkin et al. 2010; O'Conner et al. 2017, Silva et al. 2020, Mueller et al. 2021) to guide managed wildfires beyond their history of use in and near wilderness areas and closer to WUI areas to meet fuel reduction goals.

Our results also show that the number of agencies involved in managed and suppression wildfires differ significantly. This difference could be due to the larger size associated with full suppression wildfires. This pattern, however, could also be due to a reluctance of agencies to manage wildfires that will burn into adjacent agency's jurisdiction. If this is the case, our results could be a sign of a larger problem, where some agencies do not manage wildfires for resource benefit because they cannot guarantee the fire will stay within their jurisdiction.

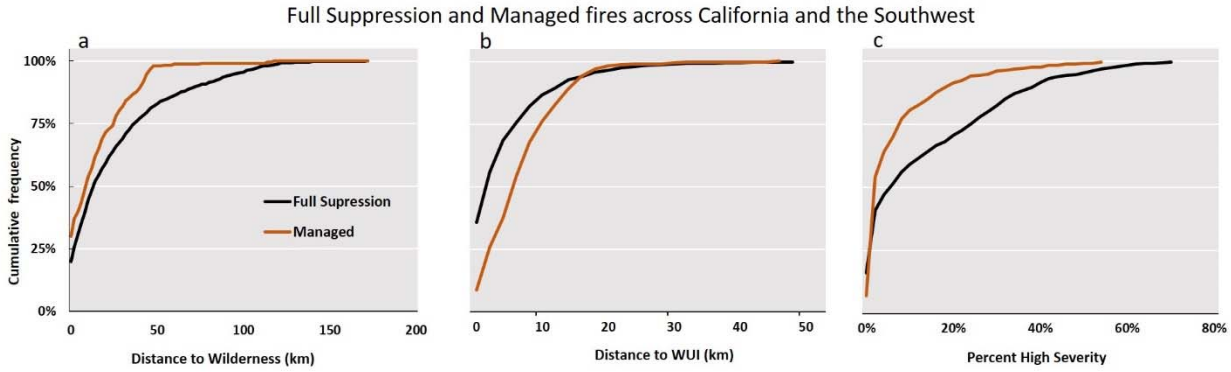

Figure 8. Comparison of full suppression (n=1180) and managed wildfires (n=254) based on (a) distance to wilderness (b) distance to WUI and (c) percent high severity within the entire study area which included the Southwest (Arizona and New Mexico) and California.

Temporal differences

Although the number of managed wildfires increased in the Southwest between 2002-2008 and 2009-2016 (49 v. 146), while the number in California declined (42 v. 17) our results show the geographic characteristics of managed wildfires remained unchanged. In both regions, the geographic properties of managed wildfires, including distance to wilderness, distance to WUI,

agencies involved, and percent high severity did not change after the 2009 Guidance was released (Fig 9 and 10). Most managed wildfires are still burning in remote locations within or near wilderness areas and away from WUI areas. Similarly, most managed wildfires still occur mainly within one or two agencies and include minimal (<5%) high severity (Fig 11). These results are in line with Young et al. (2020) which found no overwhelming change in the number or fire size of managed wildfires in California or the Southwest but did find increases in managed wildfires in other regions of the western US. As mentioned by Young et al. (2020), the lack of a temporal change in managed wildfires in the Southwest could be related to the extensive use of managed wildfires in the region prior to 2009, particularly in Grand Canyon National Park, Saguaro National Park and in the Gila National Forest. While in California the decrease in managed wildfires following 2009 is likely due to the drought this region has experienced since 2009.

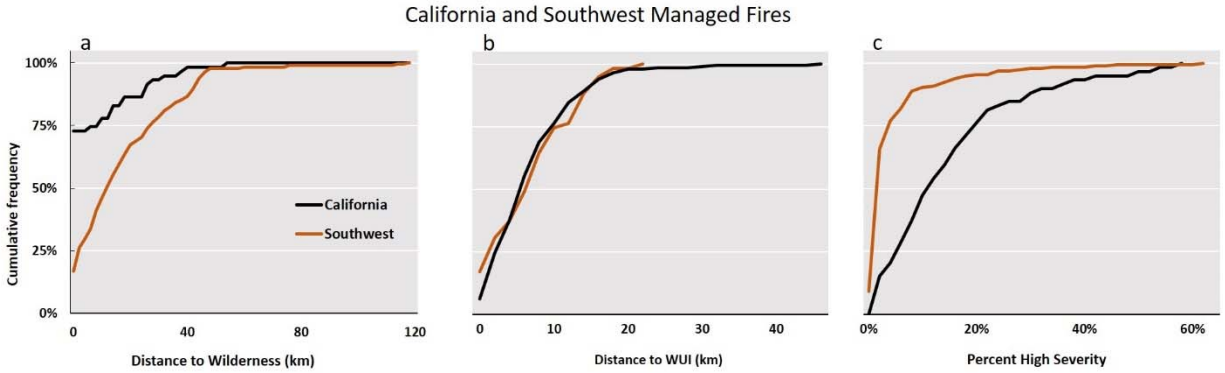

Figure 9. Comparison of managed wildfire between California (n=59) and the Southwest (n=195) based on (a) distance to wilderness (b) distance to WUI and (c) percent high severity.

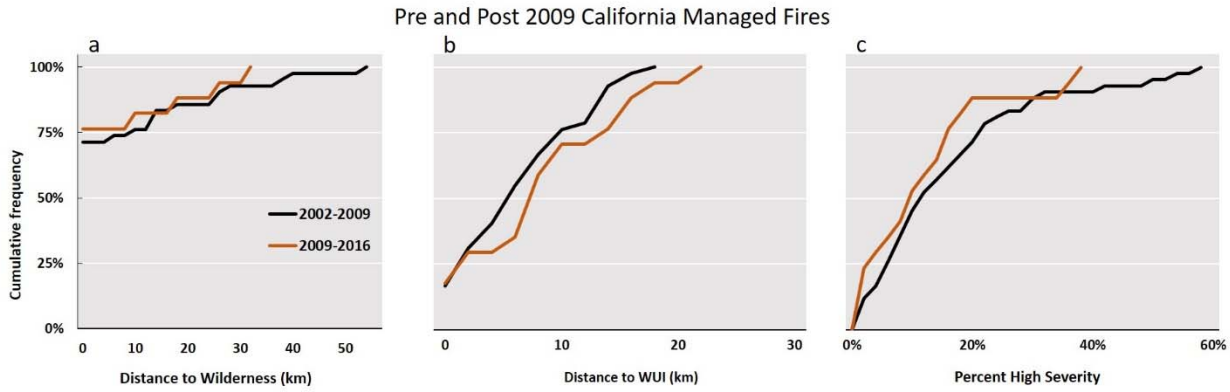

Figure 10. Comparison of managed fires in California before (2002-2008) and after (2009-2016) the 2009 policy guidance based on (a) distance to wilderness (b) distance to WUI and (c) percent high severity.

Our results show management of wildfires did not change after the 2009 policy guidance in key geographic and management metrics, suggesting that managers are still reluctant to use managed wildfires defaulting to more full suppression strategies, particularly closer to WUI. Managed wildfire in the spring and fall with minimal high severity reduces hazardous fuels,

could increase the success of a full suppression strategy during extreme burning conditions at the peak of fire season. Failure to expand the use of managed wildfires will therefore continue to lead to wildfires with more and larger high severity patches followed by a general decrease of forest cover, carbon storage and more drastic climate changes such as longer drought periods. In addition, more severe wildfires will likely affect other ecosystem services including wildlife habitat, water (including post-fire flooding), and recreation. While additional social science research is needed to better understand the social and political barriers to managed wildfires (Fillmore et al. 2021), increased support for and use of managed wildfire will be a key element in building forest and community resilience in the western U.S.

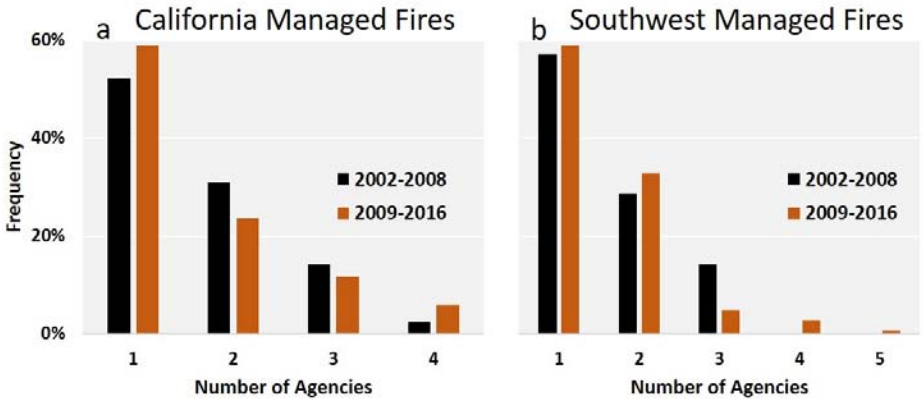

Figure 11. Number of land management agencies involved per managed wildfire compared before and after the 2009 policy guidance in (a) California and (b) Southwest.

Conclusions (Key Findings) and Management Implications

- Managed and full suppression wildfires are distinctly different in terms of where and how they burn. Strategies to manage wildfires for resource benefits are used in remote wilderness areas further from WUI, usually involve a single agency, and tend to result in lower percentages of high severity.
- In both regions (CA and SW), the geographic characteristics of managed wildfires remained unchanged after the 2009 *Policy Guidance*, including distance to wilderness, distance to WUI, agencies involved, and percent high severity.
- Most managed wildfires are still burning in remote locations within or near wilderness areas and away from WUI areas. Similarly, most managed wildfires still occur mainly within one or two agencies and include minimal (<5%) high severity percentages.

In the face of limited management options to reduce hazardous fuels in a warming climate, larger, increasing high severity wildfires in recent years highlight the inevitability of fire, albeit uncharacteristically severe wildfires, in adapted ecosystems. Reintroducing managed wildfires to forested landscapes will be an essential part of a comprehensive response needed to reduce the likelihood of devastating wildfires in the future. The lack of expanded use of managed wildfires beyond remote wilderness areas and closer to WUI, combined with the slow pace of mechanical and prescribed fire treatments as well as increasing drought conditions means that wildfires in these two regions could continue to grow even larger and more severe.

Objective 4

Our fourth objective was to identify the key social barriers and facilitators to changing wildfire management strategies and the perceptions regarding effects to high-value resources.

Research looking at factors that influence decisions to use multiple strategies rather than full suppression is also very limited (Miller and Aplet 2016). One study indicated that resource availability, and manager perceptions of negative public opinion and lack of institutional support were the main disincentives to use wildfire for resource benefit (Williamson 2007). However, another study found that a key variable is whether internal guiding documents (i.e., Land Management Plans) allow for tactical flexibility in their response choices. Other internal and external factors, such as public or manager attitudes, were not found to be as significant a barrier as expected, largely because for both groups there is a range of attitudes and expectations could be shifted with appropriate outreach (Steelman and McCaffrey 2009). In both cases, the research was conducted prior to the new policy so there is a clear need to better understand the range of barriers and facilitators that inform decisions to manage for resource benefits.

The original plan was to focus on the subsample of fires selected in Objective #1. A change to this approach was necessitated due to changes in the data available from objective #1. As we began work on Objective #4, it became clear that a subset of 40 wildfires would not meet our research goals because of the variation across wildfires was too great. We expanded our approach to include all managed wildfires during the time period. Reconsideration of these methods also lead to reconsideration of the original plan to ask agency administrators and Incident Management Team (IMT) members to remember specifics of fires from more than five years ago. Even with incident information to help recall details, the nuances of management strategy decisions were likely to become vague or mixed with subsequent wildfires over time, particularly for IMTs who are often on multiple fires every year. These reconsiderations lead to the development of a new protocol which 4, delayed the planned initiation of interviews to 2020, which then had to be postponed to 2021 due to Covid restrictions.

This new protocol focused on interviewing US Forest Service agency administrators, as well as fire managers and support staff on ongoing fires, with a focus on fires that involved some managed fire component. Agency administrators are the individuals tasked with approving the final management strategy on wildfires burning on National Forest System lands. This strategy was intended to provide both better quality and more current data and became feasible with a new addition to the research team, Stephen Fillmore, who brings both wildfire qualifications, experience, and access.

During the same period, a mixed methods review of the existing literature was conducted to increase understanding of decision-making process for managed wildfires (see Fillmore, McCaffrey, and Smith 2021). The review included research from 1976 to 2013 and employed thematic coding to identify key factors that affect the decision to manage a wildfire. The team identified 110 descriptive factors categories, which included 41 Barriers, 33 Facilitators, and 36 Unaligned elements. These factors were then into six thematic groups of decision

considerations: Institutional Influences, Operational Considerations, Fire Outcomes, Fire Environment, Perceived Risk, and Socio-Political Context. From the six themes the team built a 'Managed Fire Decision Framework' (MFDF) which contextualizes managed wildfire decision making pressures, barriers, and facilitators. All of these feed into a decision about managed wildfire. Operational concerns and risk aversion were the most prevalent obstacles to managing wildfire. In contrast, an individual decision maker's desire to see a wildfire managed with strategies other than full suppression was a key facilitating factor. The review underscored the fact that the decision-making process that leads to managed wildfire is complex and this complexity itself creates a barrier for managers.

Factors identified in this review were then used to guide a revised interview protocol that was used during the 2021 wildfire season, agency administrators were interviewed during active fires. Interviews have been completed on 15 separate wildfires. A total of 48 interviews were conducted among 34 individuals with an average of 58 minutes per interview. These individuals represented 12 different positions related to wildfire, with most interviews conducted among agency administrators, those in a fire overhead position, and members of the public (Fig. 12).

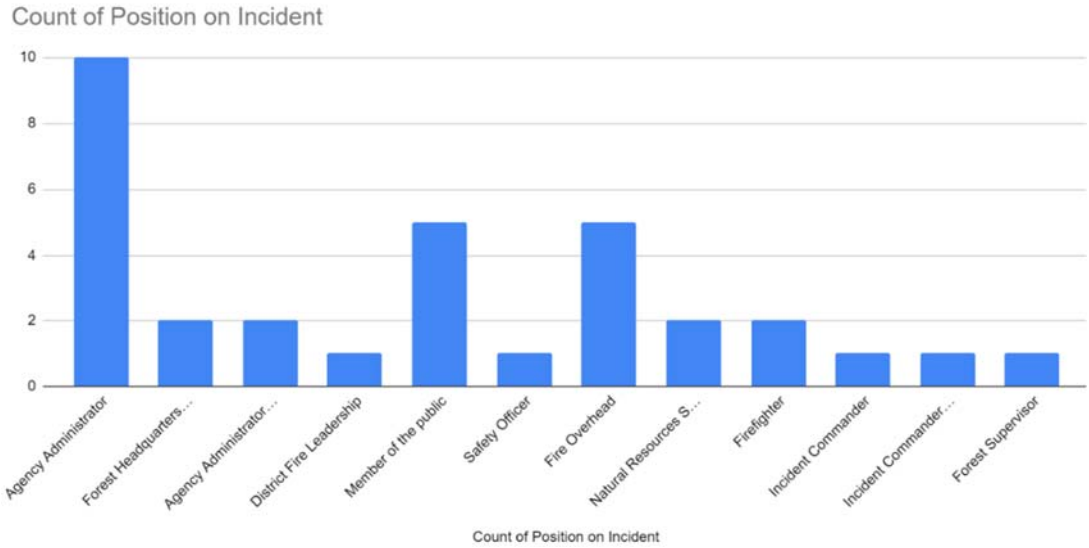

Figure 12. Frequency of positions for individuals interviewed as part of the social aspects on managed wildfires.

Analysis of the interviews that will be conducted in fall 2021 will provide empirical insights into how factors identified in the review process are weighted and considered in an actual decision processes and provide insights on differential social and institutional influences on managed wildfires. Preliminary results suggest that the rationale for managing wildfires has shifted among agency administrators since the national wildfire policy changed in 2009, and persisting sense of socio-political pressure for continuing the full suppression paradigm makes decisions to manage wildfires more challenging than polices and initiatives may otherwise suggest.

Overall Conclusions (Key Findings) and Management Implications

- Barriers to managed wildfire are dominated by environmental (burning conditions) as well as social factors including both internal (institutional) and external (public pressure).

Literature Cited

Ager AA, Evers CR, Day MA, Preisler HK, Barros AMG, Nielsen-Pincus M (2017) Network analysis of wildfire transmission and implications for risk governance. *PLoS One*. 12(3), 28. https://doi.org/10.1371/journal.pone.0172867

Balch JK, Bradley BA, Abatzoglou JT, Nagy RC, Fusco EJ, Mahood AL (2017) Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences*. 114(11), 2946–2951. https://doi.org/10.1073/pnas.1617394114

Boisramé, G., Thompson, S., Collins, B., & Stephens, S. (2017). Managed Wildfire Effects on Forest Resilience and Water in the Sierra Nevada. *Ecosystems*, 20(4), 717–732. https://doi.org/10.1007/s10021-016-0048-1

Calkin DE, Thompson MP, Finney MA (2015) Negative consequences of positive feedbacks in US wildfire management. *Forest Ecosystems*. 2(9), 10. https://doi.org/10.1186/s40663-015-0033-8

Calonico S, Cattaneo MD, Farrell MH, Titiunik R (2016) Regression Discontinuity Designs Using Covariates. Working Paper. 1-38. http://arxiv.org/abs/1809.03904

Calonico S, Cattaneo MD, Titiunik R (2014) Robust data-driven inference in the regression-discontinuity design. *Stata Journal*. 14(4), 909–946. https://doi.org/10.1177/1536867X1401400413

Cansler CA, Mckenzie D (2014) Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. *Ecol. Appl*. 24: 1037-056.

Cattaneo MD, Titiunik R, Vazquez-Bare G (2019) Power calculations for regression-discontinuity designs. *Stata Journal*. 19, 210–245.

Collins, BM (2014) Fire weather and large fire potential in the northern Sierra Nevada. *Agricultural and Forest Meteorology* 189:30–35.

Collins BM, Lyderson JM, Everett RG, Stephens SL (2018) How does forest recovery following moderate-severity fire influence effects of subsequent wildfire in mixed-conifer forests? *Fire Ecol*. https://doi.org/10.1186/s42408-018-0004-x

Collins, B. M., Miller, J. D., Thode, A. E., Kelly, M., Van Wagtendonk, J. W., & Stephens, S. L. (2009). Interactions among wildland fires in a long-established Sierra Nevada natural fire area. *Ecosystems*, 12(1), 114–128. https://doi.org/10.1007/s10021-008-9211-7

Collins, B. M., & Stephens, S. L. (2007). Managing natural wildfires in Sierra Nevada wilderness areas. *Frontiers in Ecology and the Environment*, 5(10), 523–527. https://doi.org/10.1890/070007

Collins BM, Stevens JT, Miller JD, Stephens SL, Brown PM, North MP (2017) Alternative characterization of forest fire regime: incorporating spatial patterns. Landscap Ecol. https://doi.org/10.1007/s10980-017-0528-5

Coop JD, Parks SA, Stevens-Rumann CS, Crausbay SD, Higuera PE, Hurteau MD, Tepley A, Whitman E, Assal T, Collins BM, Davis KT, Dobrowski S, Falk DA, Fornwalt PJ, Fulé PZ, Harvey BJ, Kane VR, Littlefield CE, Margolis EQ, North M, Parisien M, Prichard S, Rodman KC (2020) Wildfire-driven forest conversion in western North American landscapes. *Bioscience* https://doi.org/10.1093/biosci/biaa061

Cribari-Neto F, Zeileis A (2010) Beta Regression in R. J. *Stat. Softw*. https://doi.org/10.18637/jss.v034.i02

Dillon GK, Holden ZA, Morgan P, Crimmins MA, Heyerdahl EK, Luce CH (2011) Both topography

and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006. *Ecosphere* https://doi.org/10.1890/ES11-00271.1

Doane D, O'Laughlin J, Morgan P, Miller C (2006) Barriers to Wildland Fire Use: A Preliminary Problem Analysis. *International Journal of Wilderness*. 12, 2005–2007.

Eidenshink J, Schwind B, Brewer K, Zhu Z, Quayle B, Howard S (2007) A project for monitoring trends in burn severity. *Fire Ecol*. https://doi.org/10.4996/fireecology.0301003

Fillmore, S. D., Mccaffrey, S. M., Smith, A. M. S., & Yoder, J. (2021). A Mixed Methods Literature Review and Framework for Decision Factors That May Influence the Utilization of Managed Wildfire on Federal Lands, USA. *Fire*. https://doi.org/10.3390/fire

Fire Executive Council (2009) *Guidance for implementation of federal wildland fire management policy*. US Department of Agriculture and US Department of the Interior, Washington, DC, USA. 20.

Fites-Kaufman J, Bradley AF, Merrill AG (2006) Fire and Plant Interactions. In: 'Fire in California's Ecosystems.' University of California Press, 94-117.

Gardner RH, Milne BT, Turner M, O'Neill RV (1987) Neutral models for the analysis of broad-scale landscape pattern. *Landscape Ecol*. 1:19-28.

Gdula E, Brannfors L (2014) *Grand Canyon National Park Composite Burn Index Dataset*. Department of the Interior, National Park Service, Grand Canyon National Park.

Gustafson EJ, Parker GP (1992) Relationships between landcover proportion and indices of landscape spatial pattern. *Landscape Ecol*. 7:101-110.

Harvey BJ, Donato DC, Turner MG (2016) Drivers and trends in the landscape patterns of stand-replacing fire in forests of the US Northern Rocky Mountains (1984-2010). *Landscape Ecol*. https://doi.org/10.1007/s10980-016-0408-4

Haugo, R., Zanger, C., DeMeo, T., Ringo, C., Shlisky, A., Blankenship, K., … Stern, M. (2015). A new approach to evaluate forest structure restoration needs across Oregon and Washington, USA. *Forest Ecology and Management*, *335*, 37–50. https://doi.org/10.1016/j.foreco.2014.09.014

Hollander M, Wolfe DA (1973) *Nonparametric Statistical Methods*. New York: John Wiley & Sons. Pages 115-120.

Hu M-C, Pavlicova M, Nunes EV (2011) Zero-Inflated and Hurdle Models of Count Data with Extra Zeros: Examples from an HIV-Risk Reduction Intervention Trial. *The American Journal of Drug and Alcohol Abuse*. 37(5), 367–375. https://doi.org/10.3109/00952990.2011.597280

Huffman, D. W., Roccaforte, J. P., Springer, J. D., & Crouse, J. E. (2020). Restoration applications of resource objective wildfires in western US forests: a status of knowledge review. *Fire Ecology*. Springer. https://doi.org/10.1186/s42408-020-00077-x

Huffman DW, Sánchez Meador AJ, Stoddard MT, Crouse JE, Roccaforte JP (2017) Efficacy of resource objective wildfires for restoration of ponderosa pine (Pinus ponderosa) forests in northern Arizona. *Forest Ecology and Management*. 389, 395–403. https://doi.org/10.1016/j.foreco.2016.12.036

Hunter ME, Iniguez JM, Farris CA (2014) *Historical and current fire management practices in two wilderness areas in the southwestern United States: The Saguaro Wilderness Area and the Gila-Aldo Leopold Wilderness Complex*. USDA Forest Service, Rocky Mountain Research Station, General Technical Report, RMRS-GTR-325, Fort Collins, CO. 38.

Hunter ME, Iniguez JM, Lentile LB (2011) Short-and long-term effects on fuels, forest structure, and wildfire potential from prescribed fire and resource benefit fire in southwestern forests, USA. *Fire Ecol*. https://doi.org/10.4996/fireecology.0703108

Hunter, M. E., & Robles, M. D. (2020). Tamm review: The effects of prescribed fire on wildfire regimes and impacts: A framework for comparison. *Forest Ecology and Management*. Elsevier B.V. https://doi.org/10.1016/j.foreco.2020.118435

Imbens GW, Lemieux T (2008) Regression discontinuity designs: A guide to practice, *Journal of Econometrics*. 142(2), 615–635. https://doi.org/10.1016/j.jeconom.2007.05.001

Iniguez JM, Swetnam TW, Baisan CH (2009) Spatially and temporally variable fire regime on Rincon peak, Arizona, USA. *Fire Ecol*. https://doi.org/10.4996/fireecology.0501003

Jacob R, Zhu P, Somers M-A, Bloom H (2012) A Practical Guide to Regression Discontinuity, MDRC, Building Knowledge to Improve Social Policy.

Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DM (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*. 6, 11. https://doi.org/10.1038/ncomms8537

Kalies, E. L., & Yocom Kent, L. L. (2016). Tamm Review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review. *Forest Ecology and Management*. https://doi.org/10.1016/j.foreco.2016.05.021

Keane RE, Ryan KC, Veblen TT, Allen CD, Logan J, Hawkes B (2002) *Cascading effects of fire exclusion in the Rocky Mountain ecosystems: a literature review*. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 24.

Kelley BT (2017) *Wildland fire managed for multiple objectives in southwestern forests: Implementation obstacles*. Northern Arizona University, Thesis. 104.

Knapp EE, Estes BL, Skinner CN (2009) *Ecological effects of prescribed fire season: a literature review and synthesis for managers*. USDA Forest Service, Pacific Southwest Research Station, General Technical Report, PSW-GTR-224, Albany, CA. 78.

Kneeshaw K, Vaske JJ, Bright AD, Absher JD, Leopold A (2004) Situational Influences of Acceptable Wildland Fire Management Actions. *Society & Natural Resources*. 17, 477–489. https://doi.org/10.1080/08941920490452427

Kolden, C. A. (2019). We're not doing enough prescribed fire in the western united states to mitigate wildfire risk. *Fire*, *2*(2), 1–10. https://doi.org/10.3390/fire2020030

Lee DS, Lemieux T (2010) Regression Discontinuity Designs in Economics. *Journal of Economic Literature*. 48 (2), 281–355. https://doi.org/10.1257/jel.48.2.281

Lydersen JM, Collins BM, Brooks ML, Matchett JR, Shive KL, Povak NA, Kane VR, Smith DF (2017) Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. *Ecological Applications*. 27(7), 2013–2030. https://doi.org/10.1002/eap.1586

Margolis EQ, Swetnam TW, Allen CD (2011) Historical stand-replacing fire in upper montane forests of the Madrean Sky Islands and Mogollon Plateau, Southwestern USA. *Fire Ecol*. 7:88-107. https://doi.org/10.4996/fireecology.0703088

McGarigal K, Marks BJ (1995) *FRAGSTATS: Spatial Analysis Program for Quantifying Landscape Structure*. USDA Forest Service General Technical Report PNW-GTR-351.

Meyer, M. D. (2015). Forest fire severity patterns of resource objective wildfires in the Southern Sierra Nevada. *Journal of Forestry*, *113*(1), 49–56. https://doi.org/10.5849/jof.14-084

Meyer MD, Roberts SL, Wills R, Brooks M, Winford EM (2015) Principles of effective USA federal fire management plans. *Fire Ecology*. 11(2), 59–83.

Meyer, M.D., B. Estes, A. Wuenschel, B. Bulaon, A. Stucy, D. Smith, and A. Caprio. (2019) Structure, diversity and health of Sierra Nevada red fir forests with reestablished fire regimes. *International Journal of Wildland Fire* 28:386–396.

Miller, R. K., Field, C. B., & Mach, K. J. (2020). Barriers and enablers for prescribed burns for wildfire management in California. *Nature Sustainability*, *3*(2), 101–109. https://doi.org/10.1038/s41893-019-0451-7

Miller JD, Safford HD (2012) Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and southern Cascades, California, USA. Fire Ecology. 8(3), 41–57.

Miller JD, Thode AE (2007) Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). Remote Sens. Environ. https://doi.org/10.1016/j.rse.2006.12.006

Mueller SM, Thode AE, Margolis EQ, Yocum LL, Young JD, Iniguez J (2020) Climate relationships with increasing wildfire in the southwestern US from 1984-2015. *For. Ecol. Manage.* https://doi.org/10.1016/j.foreco.2019.117861

North M, Brough A, Long J, Collins B, Bowden P, Yasuda D, Miller J, Sugihara N (2015) Constraints on Mechanized Treatment Significantly Limit Mechanical Fuels Reduction Extent in the Sierra Nevada. *Journal of Forestry*. 113(1), 40–48. https://doi.org/10.5849/jof.14-058

North, M., Collins, B. M., & Stephens, S. (2012). Using fire to increase the scale, benefits, and future maintenance of fuels treatments. *Journal of Forestry*, *110*(7), 392–401. https://doi.org/10.5849/jof.12-021

North, M. P., York, R. A., Collins, B. M., Hurteau, M. D., Jones, G. M., Knapp, E. E., L. Kobziar, H. McCann, M.D. Meyer, S.L. Stephens, R.E. Tompkins, and Tubbesing, C. L. (2021). Pyrosilviculture Needed for Landscape Resilience of Dry Western United States Forests. *Journal of Forestry*, *119*(5), 520–544. https://doi.org/10.1093/jofore/fvab026

O'Conner CD, Falk DA, Lynch AM, Swetnam TW (2014) Fire severity, size, and climate associations diverge from historical precedent along an ecological gradient in the Pinaleño Mountains, Arizona, USA. *For. Ecol. Manage*. https://doi.org/10.1016/j.foreco.2014.06.032

Parks SA, Holsinger LM, Voss MA, Loehman RA, Robinson NP (2018b) Mean composite fire severity metrics computed with Google Earth Engine offer improved accuracy and expanded mapping potential. Remote Sensing. 10(6):879. https://doi.org/10.3390/rs10060879

Pearson GA (1923) *Natural Reproduction of Western Yellow Pine in the Southwest*. USDA For. Serv. Bullet. No. 1105.

Predictive Services (2014) ICS-209 PROGRAM (NIMS) User's Guide: Appendix C: ICS-209, Block by Block Instructions. Retrieved from https://gacc.nifc.gov/predictive_services/intelligence/niop/programs/sit_209/Help/Programs/B_209_Program/Section_5_Appendices/documents/Appendix_C.pdf

Rivera-Huerta H, Safford HD, Miller JD (2016) Patterns and trends in burned area and fire severity from 1984 to 2010 in Sierra de San Pedro Martir, Baja California, Mexico. *Fire Ecol* 12:52–72. https://doi.org/10.4996/fireecology.

Roberts SL, Kelt DA, van Wagtendonk JW, Miles AK, Meyer MD (2015) Effects of fire on small

mammal communities in frequent-fire forests in California. *J. Mammal*. https://doi.org/10.1093/jmammal/gyu011

Rudolph JE, Cole SR, Edwards JK (2018) Parametric assumptions equate to hidden observations: comparing the efficiency of nonparametric and parametric models for estimating time to AIDS or death in a cohort of HIV-positive women. B*MC Med Res Methodol* 18, 142 https://doi.org/10.1186/s12874-018-0605-8

Schmid M, Wickler F, Maloney KO, Mitchell R, Fenske N, Mayr A (2013) Boosted beta regression. *PLoS One* https://doi.org/10.1371/journal.pone.0061623

Schoennagel, T., Balch, J. K., Brenkert-Smith, H., Dennison, P. E., Harvey, B. J., Krawchuk, M. A., … Whitlock, C. (2017). Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences* 114 (18) 4582-4590 kwwsv=22grl1ruj243143:62sqdv1494:797447

Singleton M, Thode A, Sanchez Meador A, Iniguez P (2019) Increasing trends in high-severity fire in the southwestern USA from 1984 to 2015. *Forest Ecology and Management*. 433, 709–719. https://doi.org/10.1016/j.foreco.2018.11.039

Singleton, M. P., Thode, A. E., Sánchez Meador, A. J., Iniguez, J. M., & Stevens, J. T. (2021). Management strategy influences landscape patterns of high-severity burn patches in the southwestern United States. *Landscape Ecology*. https://doi.org/10.1007/s10980-021-01318-3

SIT-209 (2018) Daily Situation Reports, SIT-209 [WWW Document]. Natl. Fire Aviat. Manag. Web Appl. URL https://fam.nwcg.gov/fam-web/ (accessed 9.1.18).

Steel ZA, Koontz MJ, Safford HD (2018) The changing landscape of wildfire: burn pattern trends and implications for California's yellow pine and mixed conifer forests. *Landscape Ecol*. https://doi.org/10.1007/s10980-018-0665-5

Stephens, S. L., Collins, B. M., Biber, E., & Fulé, P. Z. (2016). U.S. Federal fire and forest policy: Emphasizing resilience in dry forests. *Ecosphere*, *7*(11). https://doi.org/10.1002/ecs2.1584

Stewart, S. I., Radeloff, V. C., Hammer, R. B., & Hawbaker, T. J. (2007). *Defining the Wildland-Urban Interface*.

Stevens JT, Collins BM, Miller JD, North MP, Stephens SL (2017) Changing spatial patterns of stand-replacing fire in California conifer forests. *For. Ecol. Manage*. https://doi.org/10.1016/j.foreco.2017.08.051

Swetnam TW (1990) Fire history and climate in the southwestern United States. Proceedings of Symposium on Effects on Fire in Management of Southwestern Natural Resources. General Technical Report RM-191. US Forest Service. 6–17.

Turner MG, Gardner RH, Dale VH, O'Neill RV (1989) Predicting the spread of disturbance across heterogenous landscapes. *Oikos* 55:121-129.

van Wagtendonk, J. W. (2007). The History and Evolution of Wildland Fire Use. *Fire Ecology*, *3*(2), 3–17. https://doi.org/10.4996/fireecology.0302003

van Wagtendonk JW, Lutz JA (2007) Fire regime attributes of wildland fires in Yosemite National Park, USA. *Fire Ecology*. 3(2): 34-52.

Villard M, Metzger JP (2014) Beyond the fragmentation debate: a conceptual model to predict when habitat configuration really matters. *J. Appl. Ecol*. https://doi.org/10.1111/1365-2664.12190

Voss M, Robinson T, Holsinger L (2018) GEE mean composite fire severity [Source code].

https://code.earthengine.google.com/c76157be827be2f24570df50cca427e9

Wahlberg M, Triepke FJ, Robbie W, Stringer SH, Vandendriesche D, Muldavin E, Malusa, J (2014) *Ecological Response Units of the southwestern United States*. USDA Forest Service Forestry Report. Southwestern Region, Regional Office, Albuquerque, NM. 201 pp.

Wibbenmeyer, M. J., Hand, M. S., Calkin, D. E., Venn, T. J., & Thompson, M. P. (2013). Risk preferences in strategic wildfire decision making: A choice experiment with U.S. wildfire managers. *Risk Analysis*, *33*(6), 1021–1037. https://doi.org/10.1111/j.1539-6924.2012.01894.x

Williams AP, Seager R, Macalady AK, Berkelhammer M, Crimmins MA, Swetnam TW, Trugman AT, Buenning N, Noone D, Mcdowell NG, Hryniw N, Mora CI, Rahn T (2014) Correlations between components of the water balance and burned area reveal new insights for predicting forest fire area in the southwest United States. *International Journal of Wildland Fire*. 24(1), 14-26. http://dx.doi.org/10.1071/WF14023

Williamson, M. A. (2007). Factors in United States Forest Service district rangers' decision to manage a fire for resource benefit. *International Journal of Wildland Fire*, *16*(6), 755–762. https://doi.org/10.1071/WF06019

Westerling ALR (2016) Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Phil. Trans. R. Soc. B* 371: 20150178. http://dx.doi.org/10.1098/rstb.2015.0178

Westerling ALR, Hidalgo HG, Cayan DR, Swetnam TW. (2006) Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science*. 313. 940-943. DOI: 10.1126/science.

Wherry LR, Meyer BD (2016) Saving Teens: Using a Policy Discontinuity to Estimate the Effects of Medicaid Eligibility. *Journal of Human Resources*, 51(3), 556–588. https://doi.org/10.3368/jhr.51.3.0913-5918r1

Wilson RS, Winter PL, Maguire LA, Ascher T (2011) Managing wildfire events: Risk-based decision making among a group of federal fire managers. *Risk Analysis*. 31(5), 805–818. https://doi.org/10.1111/j.1539-6924.2010.01534.x

Yoder, J., Engle, D., & Fuhlendorf, S. (2004). Liability, Incentives, and Prescribed Fire for Ecosystem Management. *Ecology and the Environment* (Vol. 2).

Young JD, Thode AE, Huang C-H, Ager AA, Fulé PZ (2019) Strategic application of wildland fire suppression in the southwestern United States. *Journal of Environmental Management*. 245, 504–518. https://doi.org/10.1016/j.jenvman.2019.01.003

Appendix A: Contact Information for Key Project Personnel

Jose Iniguez
USDA Forest Service
Rocky Mountain Research Station
2500 S. Pine Knoll Dr.
Flagstaff, AZ 86001
jose.m.iniguez@usda.gov

Zander Evans
Forest Stewards Guild
2019 Galisteo St. Ste N7
Santa Fe, NM 87505
Zander@forestguild.org

Andi Thode
Northern Arizona University
PO Box 15018
Flagstaff, AZ 86011
Andi.Thode@nau.edu

Sarah McCaffrey
USDA Forest Service
1033 University Place, #360,
Evanston, IL 60201
sarah.m.mccaffrey@usda.gov

Marc Meyer
USDA Forest Service
351 Pacu Lane
Bishop, CA 93514
marc.meyer@usda.gov

Shaula Hedwall
U.S. Fish and Wildlife Service
2500 South Pine Knoll Dr
Flagstaff, AZ 86001
shaula_hedwall@fws.gov

Jesse Young
USDA Forest Service
Rocky Mountain Research Station
800 East Beckwith Ave.
Missoula, MT 59801
jesse.young@usda.gov

Sepideh Dadashi Khanghah
Northern Arizona University
PO Box 15018
Flagstaff, AZ 86011
sd2273@nau.edu

Stephen Fillmore
USDA Forest Service
10845 Rancho Bernardo Rd Suite 200
San Diego, CA 92127
stephen.fillmore@usda.gov

Patrick Shin
Tacoma, WA 98402
patrick.c.shin@gmail.com

Racheal Bean
Forest Stewards Guild
2019 Galisteo St. Ste N7
Santa Fe, NM 87505
Rachel@forestguild.org

Appendix B: List of Scientific/Technical Publications/Science Delivery Products:

1. Articles in peer-reviewed journals
    a. Young, J.D., Evans, A.M., Iniguez, J.M., Thode, A., Meyer, M.D., Hedwall, S.J., McCaffrey, S., Shin, P., Huang, C.-H., 2020. Effects of policy change on wildland fire management strategies: Evidence for a paradigm shift in the western US? Int. J. Wildl. Fire 29. https://doi.org/10.1071/WF19189
    b. Singleton, Megan P., Andrea E. Thode, Andrew J Sanchez Meador, Jose M. Iniguez, Jens T. Stevens. 2021. Management strategy influences landscape patterns of high-severity burn patches in the Southwestern United States. Landscape Ecology. https://doi.org/10.1007/s10980-021-01318-3,-
    c. Fillmore, S. D., McCaffrey, S. M., & Smith, A. M. S. 2021. A Mixed Methods Literature Review and Framework for Decision Factors That May Influence the Utilization of Managed Wildfire on Federal Lands, USA. Fire https://doi.org/10.3390/FIRE4030062
    d. Iniguez, J.M., Evans A.M., Khanghah, S.D. Young, J.D., Thode, A., Meyer, M.D., Hedwall, S.J., McCaffrey, S., Fillmore. S. 2021. Changes in geographic characteristics and severity of managed wildfires following the 2009 wildfire management guidance. *In preparation*: Forests
2. Technical reports
    a. None
3. Graduate thesis (masters or doctoral)
    a. None
4. Conference or symposium proceedings scientifically recognized and referenced (other than abstracts).
    a. None
5. Conference or symposium abstracts
    a. Iniguez, Jose M., Hunter, Molly, Margolis, Ellis Q., Farris, Calvin. Fire ecology and management in the Gila NF. Frequent-Fire Forests Desired Future Conditions Workshop. Reserve, NM on 1 Aug 2017 and Silver City, NM on 3 Aug 2017.
    b. Iniguez, J.M. and S. Hedwall. Is there such a thing as too much fire? Association for Fire Ecology (invited presentation). Beyond Hazardous Fuels: Managing Fire for Social, Economic, and Ecological Benefits ~ 3rd Southwest Fire Ecology Conference. November 28-December 2, 2016. Tucson, Arizona. USA.
    c. Pooling, Megan, Thode, Andi E., and Jose M. Iniguez. Addressing Monitoring Trends in Burn Severity product limitations in the Southwest to assess increasing trends in high severity fire. Oral Presentation at: 7th International Fire Ecology and Management Congress. Orlando, FL. Nov 28-Dec 2 2017.
    d. Young, J.D., Evans, A.M., Iniguez, J.M., Thode, A.E., Meyer, M.D., Hedwall, S.J., McCaffrey, S., Shin, P., and C.H. Huang. 2020. (oral presentation) Effects of policy change on wildland fire management strategies: evidence for a paradigm shift in the western US? 8th International Fire Ecology and Management Congress: Cultivating Pyrodiversity. Tucson, AZ. 18-22 November 2019.

   e. Iniguez, J.M. (invited oral presentation) Efecto del Manejo de Incendios en la Frontera De EAU y Mexico. Ecologia y Manejo de Incendios Forestales Workshop. August 16, 2019. Saltillo, Mexico.
   f. Young, J.D., A.M. Evans, J.M. Iniguez, A.E. Thode, M.D. Meyer, S.J. Hedwall, S. McCaffrey, P. Shin, and C.H. Huang. (invited oral presentation) Effects of policy change on wildland fire management strategies: evidence for a paradigm shift in the western US? Special Session on Frontiers of wildfire on the Colorado Plateau: ecology, management, society at the 15th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region. September 9-12, 2019. Flagstaff AZ.
6. Posters
   a. None
7. Workshop materials and outcome reports
   a. None
8. Field demonstration/tour summaries
   a. Iniguez, Jose M. Effects of re-burning forest regeneration 17-years after a high severity fires. Field Trip Leader at the Burned Area Learning Network- Managing Post Fire Landscapes Field Trip Series. April 17, 2019, Flagstaff AZ. The Flagstaff field trip was conducted within a 2017 Managed fires in the Coconino and Kaibab National Forests. Field discussions were centered on managing lightning ignited fires particularly within previously burned areas.
   b. Iniguez, Jose M. and Andrea Thode. Organizing Committee members for: Burned Area Learning Network- Managing Post Fire Landscapes Field Trip Series. (April 17, 2019, Flagstaff AZ; April 23 and 24, 2019, Santa Fe, NM, May 7 and 8, 2019, Woodland Park, CO). This series of three field trips involved a number of conversations between managers and researchers regarding best practices during lightning ignited fires.
   c. Summer 2019- Consultation with the Coconino NF regarding the effects of re-burning forest regeneration after a high severity fires. The Coconino NF Silviculture Staff reached out to Andi Thode and Jose Iniguez to discuss issues related to the high mortality of seedling following prescribed and managed fires in their forests. This consultation involved a series of e-mail and field visits to discuss the topic and potential management and monitoring strategies. This consultation is on-going.
9. Website development
   a. None
10. Presentations/webinars/other outreach/science delivery materials.
   a. Meyer, M., Young, J.D.; Evans, A.; Iniguez, J.; Thode, A.E.; Hedwall, S.; McCaffrey, S. (2029). Changes in western managed fires since the 2009 Policy change. In-person presentation as the USFS Region 5 Ecology Program and Regional Forester's representative.
   b. Young, J.D.; Evans, A.; Iniguez, J.; Thode, A.E.; Meyer, M.; Hedwall, S.; McCaffrey, S.; Shinn, P.; Huang, C.H. (2019) Effects of policy change on wildland fire management strategies: Evidence for a paradigm shift in the western United

States? Presented for Southwest Fire Science Consortium Webinar Series. https://www.youtube.com/watch?v=_WTON7qEMy0 and https://www.frames.gov/catalog/62173

c. Iniguez, J.M. Fall 2018. Landscape Fire Ecology. FOR 401 Series - FOR 310 Forest Ecology for Fire Professionals. Northern Arizona University. Professor Margaret Moore. Dec 2018.
d. Iniguez, J.M. 2017. Landscape Fire Ecology. FOR 401 Series - FOR 310 Forest Ecology for Fire Professionals. Northern Arizona University. Professor Margaret Moore. Dec 2019.
e. Iniguez, Member of the Southwest Region (R3)-Rocky Mountain Research Station (RMRS) Science Advisory Inter-Disciplinary Team (SAIDT).
f. Gila National Forest. Organizing committee for Frequent-Fire Forests Desired Future Conditions Field Trip. Reserve, NM on 22 July 2018.

Appendix C: Metadata

We have submitted two metafiles generated as part of the project to the US Forest Service, Research and Development's data archive (http://www.fs.usda.gov/rds/archive/). The first metadata file (17-01-03_Young_et_al_2020_Metadata.xml) includes:

1. recompilation of data from the Incident Status Summary (ICS-209) reports database from the FAMWEB Data Warehouse, and
2. weather information for each fire related to burning conditions such as relative humidity, wind speed, and Energy Release Component (ERC).

The second metadata file (17-01-03_Iniguez_et_al_2021_Metadata.xml) focuses on data from our geospatial analysis in proximity to wilderness, WUI, land management jurisdictions, and burn severity.

As per our original data management plan, qualitative data from interviews cannot be made anonymous and will not be released, but it will be kept for at least five years on our restricted-access institutional servers, or as instructed by the IRB.