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Effects of policy change on wildland fire management strategies: evidence for a paradigm shift in the western US?

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Abstract. In 2009, new guidance for wildland fire management in the United States expanded the range of strategic options for managers working to reduce the threat of high-severity wildland fire, improve forest health and respond to a changing climate. Markedly, the new guidance provided greater flexibility to manage wildland fires to meet multiple resource objectives. We use Incident Status Summary reports to understand how wildland fire management strategies have differed across the western US in recent years and how management has changed since the *2009 Guidance for Implementation of Federal Wildland Fire Management Policy*. When controlling for confounding variation, we found the *2009 Policy Guidance* along with other concurrent advances in fire management motivated an estimated 27 to 73% increase in the number of fires managed with expanded strategic options, with only limited evidence of an increase in size or annual area burned. Fire weather captured a manager's intent and allocation of fire management resources relative to burning conditions, where a manager's desire and ability to suppress is either complemented by fire weather, at odds with fire weather, or put aside due to other priorities. We highlight opportunities to expand the use of strategic options in fire-adapted forests to improve fuel heterogeneity.

Additional keywords: decision making, dispersion, hazards, policy analysis, regression discontinuity, resource objective, wildland fire policy, zero inflation.

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Introduction

For over a century, the dominant response strategy to wildland fire in the western United States (US) has been full suppression, meaning that managers suppress fires as soon as possible to minimise fire spread. Although this approach was successful in reducing the area burned, it had the unintended consequence of homogenising landscapes as hazardous fuels accumulated (e.g. Keane *et al.* 2002; O'Connor *et al.* 2014; Taylor *et al.* 2014). In the 1970s, land managers began using natural ignitions to restore fire regimes and help reduce hazardous fuels (van Wagtendonk 2007; Hunter *et al.* 2014), particularly where mechanical treatments were not a viable option (North *et al.* 2012). Since then, federal fire policy has become increasingly flexible, with the *2009 Guidance for Implementation of Federal Wildland Fire Management Policy* (henceforth *2009 Policy Guidance*; Fire Executive Council 2009) being a significant turning point. The *2009 Policy Guidance* authorised additional autonomy and fire management flexibility for federal land-management agencies (Fire Executive Council 2009) and their state partners. A decade after its implementation, there was a need to evaluate how and where the *2009 Policy Guidance* had affected the application of fire management strategies. Our objectives were to explore 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. In addition to the area burned by individual fires, we explored what effect, if any, the *2009 Policy Guidance* had on total area burned over the course of a fire season. Each of these explorations was informed by concurrent weather and resource conditions, allowing a full examination of strategic wildland fire responses in a multifaceted fire management context.

Literature review

After a century of suppressing fires, fuels accumulation and the associated risk of high-severity fire demand increased treatments at landscape scales. In reaching treatment goals, fire is a crucial tool to improve forest conditions, reduce fuels and decrease the threat of large, high-severity wildland fires (Vaillant and Reinhardt 2017). Fire managers have used natural ignitions as a key component in the restoration of historical forest conditions and fuel loadings, with notable success after multiple fires that burned at low to moderate severity (Hunter *et al.* 2011, 2014; Huffman *et al.* 2017; SIT-209 2018). A widespread use of natural ignitions in the Grand Canyon National Park has also promoted floristic diversity (Laughlin *et al.* 2005). Similar effects have been observed in California (Stevens *et al.* 2017), where fires managed to meet resource objectives have fallen within the historical range of variability regarding burn severity, high-severity patch size and stand structure (Meyer 2015; Meyer *et al.* 2019). Yosemite National Park also has increased landscape heterogeneity and likely improved resilience to drought from increasing the use of natural ignitions (Boisramé *et al.* 2017).

Though some land managers have increasingly used wildland fires to meet resource objectives since the 1970s (van Wagtendonk 2007; Hunter *et al.* 2014), managers more commonly resort to full suppression strategies. In many instances, this was by design owing to restrictive land-management policies (Thompson *et al.* 2013; Meyer *et al.* 2015), many of which are being rewritten to be more inclusive of using wildland fires to meet resource objectives (e.g. Land and Resource Management Plan for the Coconino National Forest, USDA 2018*c*). Moreover, under the 2001 *Review and Update of the 1995 Federal Wildland Fire Management Policy*, fire managers worked under the guidance that 'wildland fires [could] either be managed for resource benefits or suppressed [and could not] be managed for both objectives concurrently' (Fire Executive Council 2009, p. 19). Additionally, once a 'fire [had] been managed for suppression objectives, it [could] never be managed for resource benefit objectives' again (Fire Executive Council 2009, p. 19). Under the *2009 Policy Guidance*, these guidelines changed dramatically when the Fire Executive Council (2009, p. 7) declared:

> 'A wildland fire may be concurrently managed for one or more objectives and objectives can change as the fire spreads across the landscape. Objectives are affected by changes in fuels, weather, topography; varying social understanding and tolerance; and involvement of other governmental jurisdictions having different missions and objectives.'

This sharp contrast in fire policy was enacted before the 2009 fire season. However, the new guidance may have been adopted over time as circumstances presented. Therefore, there is a need to explore the effects of the *2009 Policy Guidance* using multiple lines of evidence over multiple temporal windows of observation in order to fully understand its effect.

As the *2009 Policy Guidance* notes, fire managers have several factors to consider during an incident in addition to the prevailing policies. This includes an accumulation of hazardous fuels (Keane *et al.* 2002) that when combined with a warming climate and the expansion of the wildland–urban interface (WUI) has created conditions for destructive, high-severity wildland fires (Stephens *et al.* 2014; Calkin *et al.* 2015). In recent decades, the number of large fires and area burned with high severity have significantly increased (Dillon *et al.* 2011; Miller and Safford 2012; Dennison *et al.* 2014; Singleton *et al.* 2019), and the application of mechanical treatments has failed to keep pace (North *et al.* 2015). To meet the growing threat from wildland fires, the use of fire applied at large scales to perform and maintain fuels treatments needs to be increased substantially (North *et al.* 2012; Haugo *et al.* 2015; Stephens *et al.* 2016).

Several other facets also influence the use of fire. These include cognitive biases, institutional paradigms and cultural influences (Kelley 2017; Thompson *et al.* 2018), as well as fire weather (Young *et al.* 2019) and the transfer of fire across jurisdictional boundaries (Ager *et al.* 2017*b*). The fire response archetype commonly involves intuitive snap decisions that require a compromise between countervailing forces (Wilson *et al.* 2011; Hand *et al.* 2015; Thompson *et al.* 2018) during unpredictable wildland fires (Hulse *et al.* 2016), which can result in inconsistent decisions (Kahneman and Klein 2009). Alleviating the biases that run through the fire management paradigm, in part, requires the careful development of strategic fire response planning that includes clearly delineated opportunities for the deployment of successful fire control (Thompson *et al.* 2013; O'Connor *et al.* 2016, 2017; Wei *et al.* 2018).

A decision to increase the share of fires managed to meet resource objectives with strategies other than full suppression also has the potential to reduce current per hectare suppression costs (Gebert and Black 2012; Houtman *et al.* 2013). At the same time, overall suppression costs are likely to be unaffected or higher owing to increased area burned or longer management durations (Gebert and Black 2012). Nevertheless, an increase in the area burned can act as a negative fire feedback and potentially reduce future suppression costs and area burned with high-severity (Gebert and Black 2012; Houtman *et al.* 2013; Ager *et al.* 2017*a*). There are numerous other trade-offs to consider when managing wildland fires as well, including fire exposure to neighbouring landholders, the possible loss of rare or sensitive natural resources, smoke impacts to public health, suppression resource availability (e.g. human and physical capital), and a perceived and real lack of institutional and public support (Williamson 2007; Jones *et al.* 2016; Ager *et al.* 2017*a*, 2017*b*; Young *et al.* 2019). For these reasons, remote national parks and wilderness areas have presented unique opportunities to demonstrate the benefits of managing natural ignitions to meet resource objectives (Barnett *et al.* 2016; Miller and Aplet 2016; SIT-209 2018). Other natural ignitions managed to meet resource objectives on National Forests commonly occur during shoulder fire seasons, resulting in low-severity burns with limited benefit from a single entry (Huffman *et al.* 2017).

Methods

The *2009 Policy Guidance* empowered federal land management agencies and their state partners with greater flexibility to use natural ignitions to meet resource objectives using strategies other than full suppression. A decade after its implementation, there was a need to evaluate how and where this policy had affected the application of fire management strategies. To this end, 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 historic and current fire management policy suggests (Fire Executive Council 2009, p.18; Predictive Services 2014, p. 17), 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, we compiled Situation Reports (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 9238 fires. Constituents of a fire complex were identified using an algorithm, and duplicate fires were identified with a visual examination of fires that ignited within 20 days of each other, 111 km (69 miles) of each other, and had the same leading name (e.g. *Table* Fire, *Table* Mountain and *Table* Mountain Fire). We also removed other known duplicate fires (e.g. Chediski Fire of the Rodeo–Chediski). In total, we identified 2154 small fires (<40.5 ha (100 acres)) and 7084 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). The small-fire population within the SIT-209 reports, while informative, has a known reporting bias due to the omission of fires that were quickly suppressed with initial attack actions, or otherwise failed to reach SIT-209 reporting thresholds (USDOI/USDA 2011). For this reason, small fires were removed from our formal statistical evaluations.

For the western US and each subregion, we performed a set of separate analyses. First, we summarised 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, $Y_{i\,\text{'}Suppression\text{'}}$) and fires predominantly managed with strategies other than full suppression (noted herein as 'other' strategies or fire, $Y_{i\,\text{'}Other\text{'}}$).

2009 Policy Guidance (P)

In February 2009, the Fire Executive Council, composed of officials from the USDA and the USDOI, issued the *Guidance for Implementation of Federal Wildland Fire Management* to address an insufficient implementation of current wildland fire policy (Fire Executive Council 2009; Schultz *et al.* 2019). This guidance was implemented immediately on publication through federal land-management agencies within the USDA and USDOI and through the National Wildfire Coordinating Group (Fire Executive Council 2009, p. 4). 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.

We expected the increased flexibility of the *2009 Policy Guidance* to increase the use of 'other' management strategies on large fires ($Y_{1\,\text{'}Other\text{'}}$). As follows, we contrarily expected the *2009 Policy Guidance* to result in a reduction in 'suppression' fires ($Y_{1\,\text{'}Suppression\text{'}}$), *ceteris paribus*. Our expectations of the effect on management duration (Y_2) and area burned by individual large fires (Y_3) and by all large fires within a fire year (Y_4) were based on the relative importance of the aforementioned shifting strategic response (Y_1) and changes in fire management where the *2009 Policy Guidance* would not have affected the fire's classification. That is, if shifting strategic responses are the dominant effect, we would expect the potential transfer of the shortest-duration 'suppression' fires to the 'other' fire classification to increase the average duration and area burned of 'suppression' fires ($Y_{2,3\,\text{'}Suppression\text{'}}$). We further expect the duration and size of 'other' fires ($Y_{2,3\,\text{'}Others\text{'}}$) to depend on the relative burning conditions between fires with a shifting strategic response and fires that would have been managed with 'other' strategies regardless of the *2009 Policy Guidance*. For example, although we may expect marginal fires with a shifting strategic response to be longer and larger as the result of the *2009 Policy Guidance* ($Y_{2,3\,\text{'}Other\text{'}}$), these fires are likely to burn under conditions that are not conducive to fire growth, limiting their duration and fire size. However, regardless of these relative conditions, it is conceivable to observe a policy-driven increase

Table 1. Variables and units used in our analyses. The SIT-209 fields have changed through time

Variables (fire units, 'fire year' units)	SIT-209 fields, description		Years
Situation Reports (SIT-209)			
DISCOVERY DATE (day of year, mean day of year)	Start date		2002–13
	Discovery date		2014–16
	Date of first report (as needed)		–
CONTROL DATE (day of year, mean day of year)	Control date		2002–13
	Anticipated completion date		2014–16
	Date based on criterion (as needed)[B]		–
FIRE SIZE (hectares, total hectares)	Area		2002–13
	Current incident area		2014–16
HOUSES AT RISK (count, total count)[A]	Primary houses		2002–13
	Single-unit residence		2014–16
	Multi-unit residence		2014–16
	Mixed commercial and residential		2014–16
COMMERCIAL BUILDINGS AT RISK (count, total count)[A]	Commercial building		2002–13
	Non-residential commercial		2014–16
	Mixed commercial and residential		2014–16
OTHER BUILDINGS AT RISK (count, total count)[A]	Outbuildings		2002–13
	Other structures		2014–16
INJURIES (count, total count)	Injuries to date		2002–13
	Public and responder injuries, illness		2014–16
FATALITIES (count, total count)	Fatalities		2002–13
	Public and responder fatalities		2014–16
CAUSE ((0 = natural; 1 = human), human-caused count)	Cause		2002–13
	Cause identifier		2014–16
NUMBER OF FIRES – REGION (count)	Count of large regional fires		2002–16
NUMBER OF FIRES – WEST (count)	Count of large western US fires		2002–16
DISCOVERY YEAR (count)	Year of discovery		2002–16
Remote Automated Weather Station (RAWS)		Individual fire	'Fire year'[C]
Energy Release Component (ERC)	British thermal units per square foot released from a fire's flaming front	Median day	Median fire in the 'fire cluster' each 'fire season' by fire type
Average Relative Humidity (AvgRH)	Daily average water vapour in the air relative to saturation	Mean day	Mean fire in the 'fire cluster' each 'fire season' by fire type
ERC × AvgRH	Expected fuel moisture proxy	–	–
PRECIPITATION	Daily precipitation (inches[D])	Fire total	Total for all fires in the 'fire cluster' each 'fire season' by fire type
WIND	Daily average wind speed (miles per hour)	Median day	Median fire in the 'fire cluster' each 'fire season' by fire type
PRECIPITATION × WIND	Stormy weather proxy	–	–
Maximum Vapour Pressure Deficit (VPD)	Pressure of atmospheric demand for water (Pascals)	Mean day	Mean fire in the 'fire cluster' each 'fire season' by fire type

[A]For each structure type, we assessed the total count of structure-threatened-days for each individual fire, which was then aggregated across 'fire clusters' within 'fire seasons' for the 'fire year' models.
[B]For criterion description, see Appendix A1.2, Supplementary material.
[C]See *Observational units* and Table 2 for a description of a 'fire year'.
[D]To convert estimated effects (EE) from Tables 7 and 8 to tenths of inches: $(((EE/100 + 1)^{0.1}) - 1) \times 100$.

in total area burned of 'other' fires ($Y_{4\,\text{‘Other’}}$) if a large number of fires shifted due to *2009 Policy Guidance*. Under the condition that the dominant policy effect is from fires that would have been managed with 'other' strategies regardless, we would expect the management duration and area burned of 'other' fires individually and in total to increase ($Y_{2,3,4\,\text{‘Other’}}$). Contrarily, under this condition we would not expect did not expect the *2009 Policy Guidance* to affect the management duration and area burned by individual 'suppression' fires or area burned in total ($Y_{2,3,4\,\text{‘Suppression’}}$). For additional information on the classification of wildland fires ($Y_{1\,\text{‘Suppression’},\text{‘Other’}}$) and the derivation of management duration ($Y_{2\,\text{‘Suppression’},\text{‘Other’}}$) and area burned ($Y_{3,4\,\text{‘Suppression’},\text{‘Other’}}$) refer to Table 1 and Appendix A1, available as Supplementary material to this paper.

Though the effects of the *2009 Policy Guidance* as it relates to its timing of implementation are the primary interest of our study, several concurrent advancements are inextricably linked, and therefore each contributes to our estimated effects. Most notable is the release of the Wildland Fire Decision Support System (WFDSS), which informs fire management decisions based on spatially located assets and probabilistic fire simulations (USDA 2008, 2018*b*). Other advancements include increasingly integrated fire management planning (Acuna *et al.* 2010; O'Connor *et al.* 2017; Wei *et al.* 2018) and potential land management cost savings as land managers become less risk-averse (Thompson *et al.* 2013; Wibbenmeyer *et al.* 2013; Schultz *et al.* 2019).

Changes in wildlife habitat, site-specific fuel loading or smoke management policies can affect fire management strategies and are potential sources of confounding variation that are not controlled for in our analyses (Long *et al.* 2017). In contrast, structural relationships that are consistent across our dataset (2002 to 2016) would not confound our estimates of structural policy effects. This includes the application of 'other' strategies in wilderness areas (Hunter *et al.* 2014) or in areas that cannot be readily managed with a 'suppression' strategy (e.g. remote canyons regardless of wilderness designation).

It is also possible that policy effects captured within our analyses suffer from endogeneity (i.e. the *2009 Policy Guidance* was implemented to reflect the prevailing application of fire management strategies). For several reasons, this is not likely to be the case. First, in many regions, there is still a prevailing bias towards the status quo of limiting the time exposure of potential negative effects of fire with a 'suppression' strategy (Thompson *et al.* 2018), which is consistent with prevailing attitudes before the *2009 Policy Guidance* (e.g. Wilson *et al.* 2011; Wibbenmeyer *et al.* 2013). Second, cognitive biases are confounded by the growing share of fire management costs consuming state and federal land-management budgets. For example, the US Forest Service's expenditures going to fire management has increased from 16% of the annual budget in 1995 to 52% in 2015 (USDA 2015). Under these conditions, it is unlikely that the application of 'other' strategies was beginning to replace the use of a 'suppression' strategy before 2009, because management costs under 'other' strategies are likely to be unaffected or higher (Gebert and Black 2012). Third, a primary concern of endogeneity is self-selection. But, notably, the application of all 'other' management strategies is self-selective owing to the status quo bias of using 'suppression' strategies, a bias intended to be relieved by the *2009 Policy Guidance* through enabling the consideration of 'other' strategies before 'suppression'. This dilutes the potential for endogenous effects of any real concern, especially when using a regression discontinuity design (Antonakis *et al.* 2014) known to deliver robust causal inferences comparable with experimental approaches in the presence of endogeneity (Cook 2008; Kim and Steiner 2016) because the model's error is uncorrelated with the treatment variable (i.e. post-treatment timeframe from 2009 to 2016; Antonakis *et al.* 2014).

In addition, we did not detect any evidence that the application of fire management strategies ('suppression' *v.* 'other') would have been affected by a potential decline in fire management funding levels during the Great Recession that began in 2008. Contrarily, from 2002 to 2016, there was a close relationship between wildland fire suppression costs across all ownerships in the US (in 2016 dollars), and the number of large fires (Y_1) and total area burned (Y_4) across the western US annually (Spearman's correlation coefficient: number of fires $(Y_1) = 0.43$, $P = 0.12$; total area burned $(Y_4) = 0.61$; $P = 0.02$) (USDOI/USDA 2019).

Wildland fire (F)

For each individual fire, we collected variables from SIT-209 reports that are connected to the application of fire management strategies (Table 1). 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 documented in several studies throughout the western US (Westerling *et al.* 2006; Miller and Safford 2012; Westerling 2016; Singleton *et al.* 2019). A description of each wildland fire variable can be found in Table 1, and a discussion of the expected relationship between each variable and response ($Y_{1,2,3,4}$) can be found in Appendix A2.1 (Supplementary material).

Fire weather (W)

We collected weather data from 779 Remote Automated Weather Stations (RAWS) across 137 Predictive Service Areas (PSAs) of the western US (https://gacc.nifc.gov/swcc/predictive/predictive_services.htm, last accessed 23 June 2020). 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 and over periods with active fire management within a 'fire cluster' over the course of a 'fire season', i.e. 'fire year' (Tables 1 and 2).

Based on prior research and conversations with fire managers, we expected fire weather effects to be co-dependent (i.e. conditioned) on each other (Young *et al.* 2019), which supported the inclusion of interaction terms (Brambor *et al.* 2006). This included effects of the energy release component (ERC) interacting with average relative humidity (AvgRH) to capture expected fuel moisture (van Wagtendonk 2006), and the effects of PRECIPITATION interacting with WIND to capture stormy weather (Young *et al.* 2019). A description of each fire weather variable can be found in Table 1, and a discussion of the expected relationship between each variable and response ($Y_{1,2,3,4}$) can be found in Appendix A2.2 (Supplementary material). Appendix B, Table B1 (Supplementary material) contains summary statistics for all variables included in our analyses.

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). Owing to our separate analyses of 'suppression' and 'other' fires, we assumed fire managers were aware of and complying with the *2009 Policy Guidance*, and for this reason a fuzzy regression discontinuity design was not pursued (Jacob *et al.* 2012). However, owing to the highly stochastic nature of wildland fires (Finney *et al.* 2011; Hulse *et al.* 2016), we allowed an ample amount of time for policy adoption through the application of uniform (rectangular) kernel weighting in our local (non-parametric) models via 3-year (2006–08 *v.* 2009–11) and 6-year bandwidths (2003–08 *v.* 2009–14), and through the retention of each fire in our global (parametric) models (2002–08 *v.* 2009–16). Six-year bandwidths and global models examine extended time frames that include the strategy of Monitor introduced in 2012 (SIT-209 2018). Monitor is defined as the 'systematic process of observing, collecting and recording fire-related data' while allowing the fire to burn naturally (Predictive Services 2014, p. 2).

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.* 2019). 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 ($Y_{i\,\text{'Other'}}$). 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) (Appendix B, Table B2, Supplementary material). The Rocky Mountains are also discussed based on robust effects within our global SRD framework.

We assessed the internal validity of our SRD design and the consistency of our fire classification across the western US with univariate local models of fire weather for each fire classification individually ('suppression' and 'other') and combined (Imbens and Lemieux 2008; Jacob *et al.* 2012). If the classification of 'suppression' and 'other' fires (which is based on management reporting) was not affected by the *2009 Policy Guidance*, then there is little evidence to support that changes in fire management after the *2009 Policy Guidance* were driven by reporting. The univariate weather models performed according to our expectations, and most variables did not show a significant change within fire classifications ('suppression' and 'other') due to the implementation of the *2009 Policy Guidance*. Refer to Appendix A3.1 (Supplementary material) for an extended discussion of our univariate weather models.

Table 2. Observational units for each of the four response variables in our analyses

Response variable (Y_i); unit	Observational unit – description
Management duration (Y_2); days Area burned (Y_3); hectares	Individual fire – each fire results in a single fire observation of its type ('suppression' and 'other')
Number of fires (Y_1); count Total area burned (Y_4); hectares	'Fire year' – each 'fire season' a wildland 'fire cluster'[A] has at least one fire, it results in a pair of 'fire year' observations, one for each fire type ('suppression' and 'other')

[A]There are a total of 779 wildland 'fire clusters' based on the origin of the weather data (i.e. Remote Automated Weather Stations, RAWS) within Predictive Service Areas (PSAs): California (226), Great Basin (92), Inland Empire (154), Northwest (144), Rocky Mountains (88) and Southwest (108). Note: Some 'fire clusters' span regions.

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 (Table 2). 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 area burned (Y_4) by each fire classification, we used 'fire years' (Table 2). 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 observational units resulted in zero inflated data for both '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). Refer to Appendix A3.2 (Supplementary material) for additional considerations made for our global models.

Results

Small wildland fires (<40.5 ha)

Since the implementation of the *2009 Policy Guidance*, the number of small 'suppression' fires (<40.5 ha) inclusive of

Table 3. Number of small wildland fires (<40.5 ha) for each region in the western US pre-*Policy Guidance* (2002 to 2008) and post-*Policy Guidance* (2009 to 2016)

Small fires without strategies: California, 4; Northwest, 2; Southwest, 1

	'Suppression' fires		'Other' fires	
	pre-*Policy Guidance*	post-*Policy Guidance*	pre-*Policy Guidance*	post-*Policy Guidance*
California	605	217	0	6
Great Basin	28	20	77	72
Inland Empire	86	53	243	279
Northwest	27	38	15	38
Rocky Mountains	16	31	47	157
Southwest	11	25	5	51
Western US	773	384	387	603

federal and state management that met the threshold of SIT-209 reporting (USDOI/USDA 2011) has been cut in half, while the number of 'other' fires has increased substantially in as many years (Table 3). A 'suppression' strategy was used to manage the majority of small fires pre-*Policy Guidance* in California (100%), Northwest (64%) and Southwest (69%). At the same time, 'other' strategies were dominant in the Great Basin (73%), Inland Empire (74%) and Rocky Mountains (75%). During the post-*Policy Guidance* period, California was the only region where 'suppression' remained the dominant strategy (97%), while all other regions managed at least half of small fires with 'other' strategies. In fact, the proportion of small 'other' fires in the Southwest increased 2-fold after 2009 compared with before (Table 3, 5/16 *v.* 51/76).

Large wildland fires (≥40.5 ha)

From 2002 to 2016, the number of total and 'suppression' large fires in the western US, inclusive of federal and state management, fluctuated widely, with local maximums approximately every 5 to 6 years (Fig. 1). 'Other' fires represent a smaller portion of total fires, with a peak in 2009 (32% = 140 of 435 fires). The 'suppression' fires represent between 68% (2009 with 295 fires) and 96% (2002 with 450 fires) of large fires per year, with an average of 86%. Since 2002, the number of total fires and 'suppression' fires has been decreasing in California, while the number of 'other' fires has been increasing in the Inland Empire, Rocky Mountains and Southwest (Fig. 2).

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%. 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

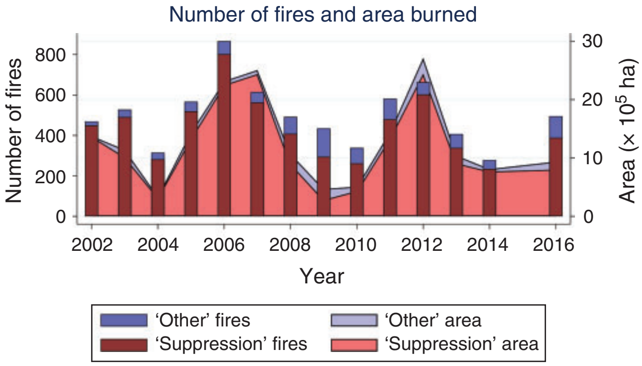

Fig. 1. Number of large wildland fires (≥40.5 ha) and area burned (ha) by dominant strategy from 2002 to 2016 in the western US. The stacked bars represent the number of wildland fires per year (left *y* axis), where the red ribbons symbolise 'suppression' fires and the blue ribbons symbolise 'other'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

Southwest, particularly in 2003 (70 638 ha), 2009 (114 325 ha) and 2016 (74 511 ha).

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.

2009 Policy Guidance – *SRD results*

The *2009 Policy Guidance* had a significant effect on the application of 'suppression' and 'other' strategies on large wildland fires as assessed by our local and global SRD models. We focus on 'other' large fires, with a change in odds of a 'fire year' only containing 'other' fires after the *2009 Policy Guidance* being derived from the zero inflated step of the global model assessing total area burned by 'suppression' fires (refer to Appendix A3.2, Supplementary material, for detailed methods). We present results from the western US and three subregions: Inland Empire, Rocky Mountains and Southwest.

For each study area, we explored multiple bandwidths and modelling procedures to balance precision with consistency (accuracy) and to explore the sensitivity of our results. Widening the bandwidth of local SRD models improves precision by increasing the sample size, but a narrow bandwidth is more consistent and less biased if there is a large number of observations in close proximity to the policy treatment (Imbens and Lemieux 2008; Lee and Lemieux 2010). We also fitted

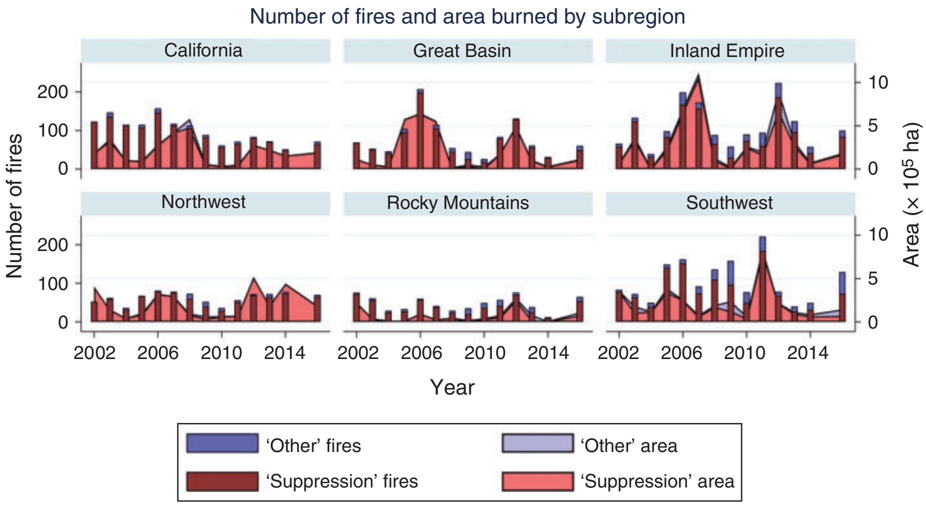

Fig. 2. Number of large wildland fires (≥40.5 ha) and area burned (ha) by dominant strategy from 2002 to 2016 for each subregion. The stacked bars represent the number of wildland fires per year (left *y* axis), where the red ribbons symbolise 'suppression' fires and the blue ribbons symbolise 'other'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

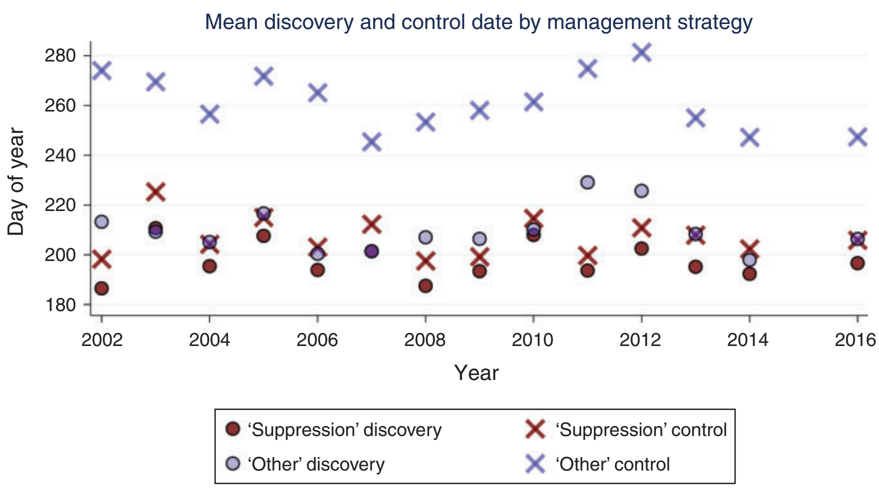

Fig. 3. Mean discovery and control dates for large 'suppression' and 'other' fires (≥40.5 ha) in the western US. For non-leap years: Day 180 = 29 June; Day 220 = 8 August; Day 260 = 17 September.

quadratic models to relieve linear constraints that are best suited to narrow bandwidths, which can improve performance and reduce bias (Lee and Lemieux 2010). However, the incorporation of highly variable data that are sparsely populated and/or far removed from the cut-off point can call into question the consistency of quadratic estimations. Auspiciously, in the case of inconsistent quadratic estimations and a limited number of observations, a correct specification of the data's distribution within global SRD models improves efficiency by recovering hidden observations (Rudolph *et al.* 2018). For each of these reasons, we assess the sensitivity of our results across multiple bandwidths in local linear, local quadratic and global SRD models, where each must be judged on its own merits and among its peers. For example, our local quadratic models with 3-year bandwidths use sparsely populated data with high variability and commonly appear inconsistent when compared with many of their peers that are in agreement. Inconsistent models should be interpreted with caution, and their peer models should be in the forefront. When all models generally agree in their identification of a significant effect, the estimated policy effect is robust to alternative model specifications, increasing our confidence in their interpretations.

Western US When examining 'fire years' with local SRD techniques in the western US, our significant univariate models estimated an average increase of 0.19 to 0.21 'other' fires per 'fire year' following the *2009 Policy Guidance* (Fig. 4). When

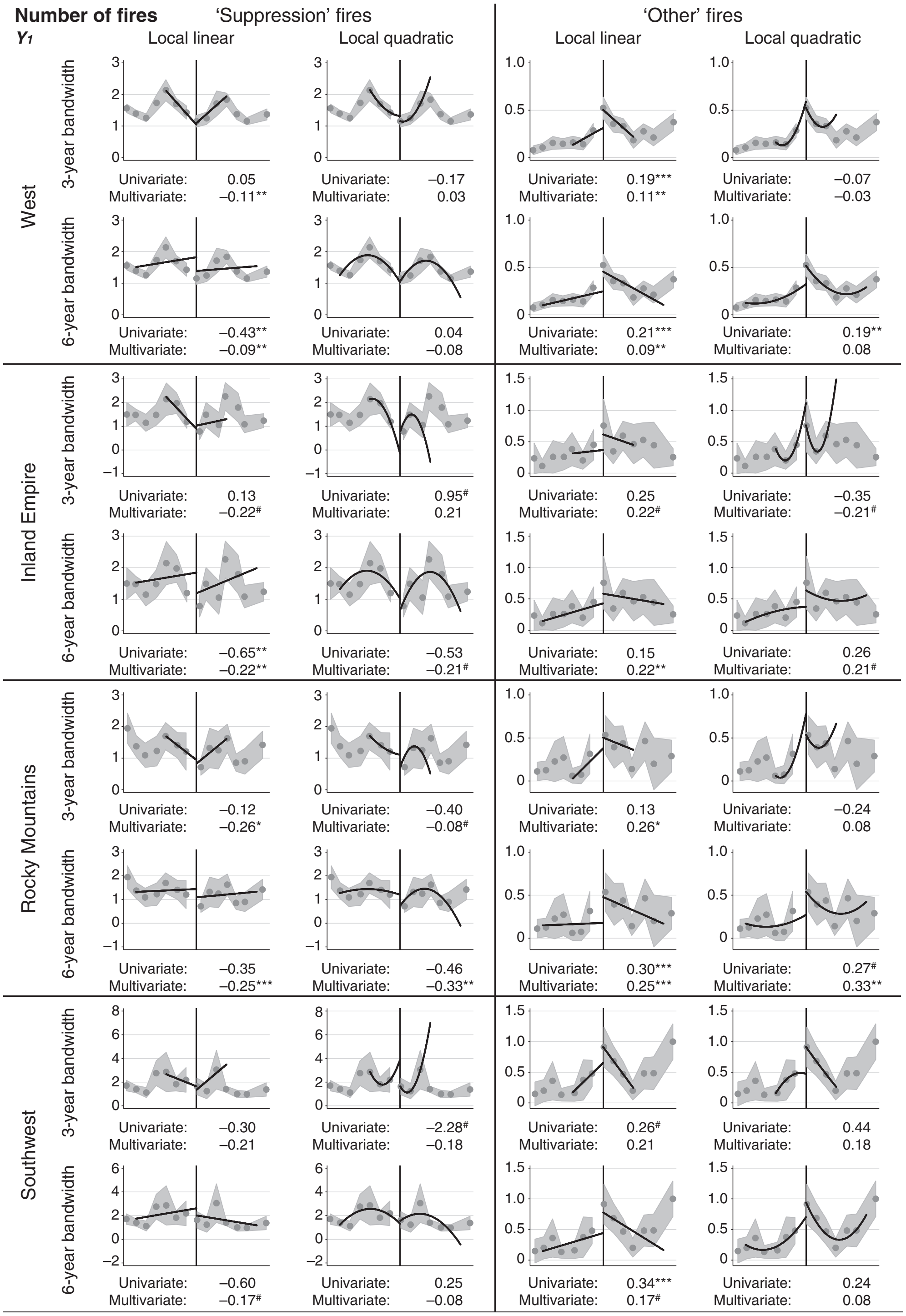

Fig. 4. Local sharp regression discontinuity (SRD) effects of the *2009 Policy Guidance* on the number of fires per 'fire year' (Y_1). The *y* axis units are number of fires. The vertical line within each plot separates pre-*Policy* (2002 to 2008) and post-*Policy* (2009 to 2016) timeframes. Points represent evenly spaced binned data that mimic the data's variance using spacing estimators, with a 95% confidence interval shown by the shaded area. Lines represent univariate *Policy* effects. Below each figure are univariate and multivariate estimates of the *Policy* effect and significance levels with clustered standard errors based on 'fire clusters'. $^{\#}$ $P < 0.2$; * $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$.

Table 4. Effects of the *2009 Policy Guidance* (γ) on the number of fires (Y_1) and total area burned (Y_4) using a global sharp regression discontinuity (SRD) framework with covariates (i.e. multivariate models)

Policy effects for 'suppression' and 'other' fire samples are estimated with count modelling procedures. The %Δ in the number of fires (Y_1) and total area burned (Y_4) of 'suppression' and 'other' fires are estimates of how the *2009 Policy Guidance* has affected these metrics for the average 'fire year' from 2009 to 2016 compared with 2002 to 2008. Estimates of significance are calculated for two clustering methods: by 'fire cluster' to control for spatial heterogeneity, and by 'fire season' to control for temporal heterogeneity. Insignificant results should be interpreted as no detectable change regardless of the listed value. We used jack-knife simulations to evaluate the robustness of significant estimates with respect to space and time (superscripts in parentheses signify the number of replicates that failed to converge and were not included in jack-knife estimates of policy significance). Insignificance as assessed by jack-knife simulations lends evidence for a policy effect that was limited in space and/or time. Estimated effects from the zero inflated (ZI) model step (where applicable) are reported in Table B7. POIS, Poisson; ZIP, zero inflated Poisson; ZINB, zero inflated negative binomial. Number of 'fire years' (n): Western US = 3750; Inland Empire = 775; Rocky Mountains = 406; Southwest = 595. # $P < 0.2$; * $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$

Response variable Regions	'Suppression' fires %Δ	Fire cluster	Fires season	Model	'Other' fires %Δ	Fire cluster	Fires season	Model
Number of fires (Y_1)								
Western US	0%			ZINB[A]	+27%	*		ZIP
Inland Empire	0%			ZINB	+81%	***(**^{1})	***	ZIP
Rocky Mountains	−24%	*(*)	***	POIS	+275%	***(***)	***(**)	POIS
Southwest	−3%			ZINB	+9%			POIS
Total area burned (Y_4)								
Western US	+23%			ZINB	+19%			ZINB
Inland Empire	+43%			ZINB	−25%			ZINB
Rocky Mountains	+45%		*	ZINB	+144%	#	*	ZINB
Southwest	+0%			ZINB	+10%			ZINB

[A]Assessed with the removal of HOUSES AT RISK from the ZI model step for convergence.

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 0.08 to 0.11 'other' fires per 'fire year' (Fig. 4). This represents an estimated 53 to 73% increase compared with the average of 0.15 'other' fires across 'fire years' in the western US from 2002 to 2008 (e.g. 53% = $(0.08/0.15) \times 100$). 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. 4). For comparison, our global SRD count model estimated a 27% increase in the number of fires being managed with 'other' strategies in receptive 'fire clusters' (Table 4). 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 (Fig. 5). 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 (Table 5). This effect was determined to be robust across space and time (jack-knife validated across 'fire clusters' ($P < 0.01$) and 'fire seasons' ($P < 0.01$)). Contrarily, we did not detect an increase in management duration with quadratic models, or a 3-year bandwidth that assessed the policy's effect before the 'other' strategy of Monitor was introduced in 2012. Likewise, we did not detect a significant change in the area burned by 'other' fires individually or in total within 'fire years'.

Inland Empire Local linear models (with the exception of the quadratic model with a 3-year bandwidth) detected a 0.21 to 0.22 fire increase in 'other' fires per 'fire year' in the Inland Empire (Fig. 4), an increase of 78 to 81% compared with the average of 0.27 'other' fires across 'fire years' from 2002 to 2008. Similarly, global models estimated an 81% increase in the number of 'other' fires with robust effects across 'fire clusters' (Table 4). Individual 'other' fires also experienced a 7- to 10-day increase in their management duration as assessed by local linear and quadratic models with 6-year bandwidths (Fig. 5). This equates to a 10 to 14% increase compared with 71 days, the average duration of 'other' fires from 2002 to 2008. The global model estimated a 20% increase in management duration of individual 'other' fires in a limited number of 'fire years' (Table 5). Similar effects were not identified by our local models using a 3-year bandwidth, which analyses policy effects before the Monitor strategy was introduced in 2012. When assessing area burned by individual fires, we did not find a significant effect (Fig. 6). However, when we used a local linear model with a 6-year bandwidth to examine total area burned by 'other' fires within 'fire years', we detected a 1200-ha increase (Fig. 7), which equates to a 260% increase compared with 462 ha, the average area burned by all 'other' fires within 'fire years' from 2002 to 2008. A similar increase in total area burned was not detected with any other models.

Rocky Mountains We detected a 0.25 to 0.33 fire increase in 'other' fires per 'fire year' in the Rocky Mountains in our local linear and quadratic models (with the exception of the quadratic model with a 3-year bandwidth) (Fig. 4). This is a 167 to 220% increase compared with the average of 0.15 'other' fires across 'fire years' from 2002 to 2008. Similarly, global models estimated a robust 275% increase in the number of 'other' fires (Table 4). Local linear and quadratic models, with the exceptions of the local linear model with a 6-year bandwidth, detected a 1102- to 4810-ha increase in area burned by individual 'other' fires per 'fire year' (Fig. 6), which equates to a 192 to 839%

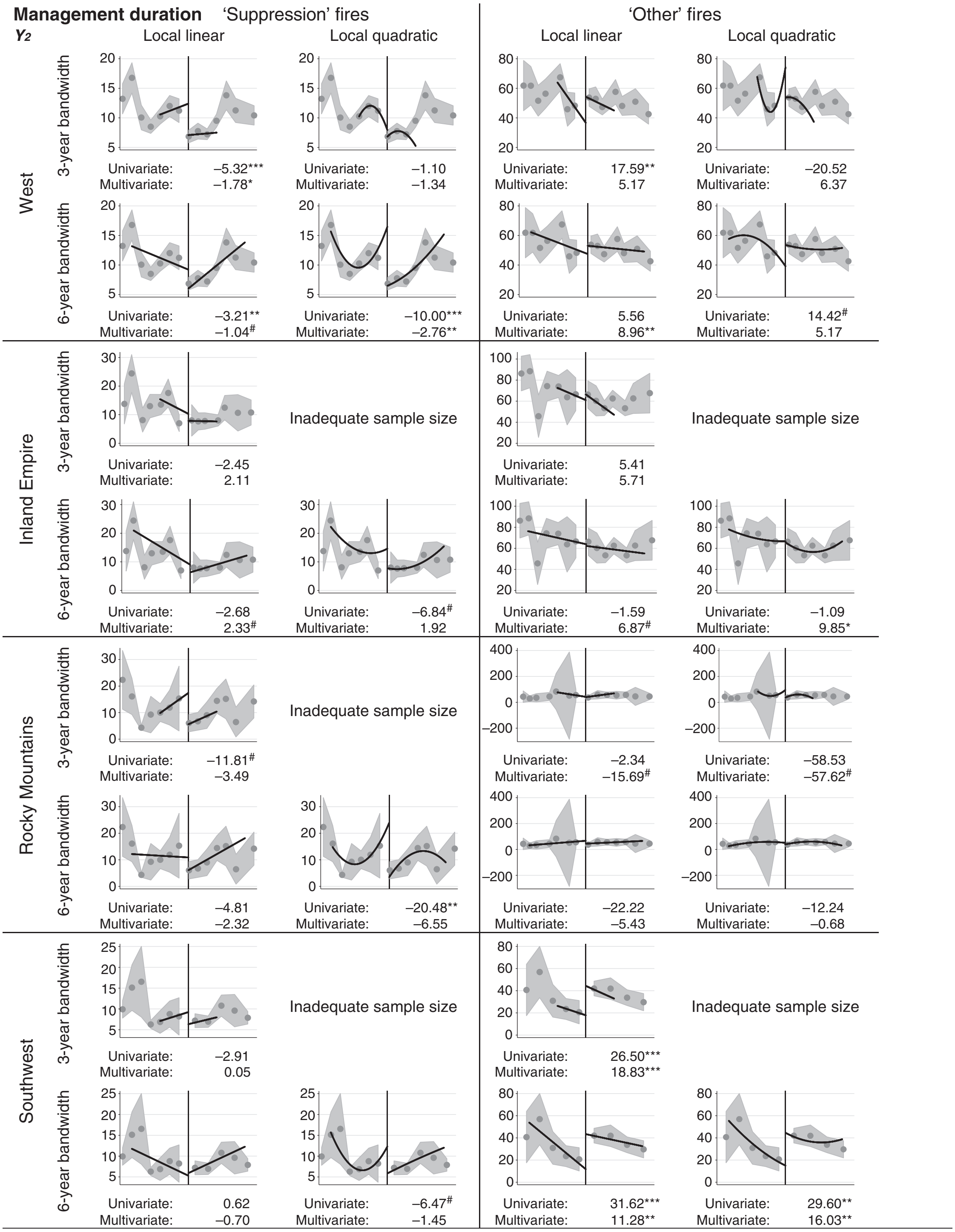

Fig. 5. Local sharp regression discontinuity (SRD) effects of the *2009 Policy Guidance* on the management duration per fire (Y_2). The y axis units are number of days. The vertical line within each plot separates pre-*Policy* (2002 to 2008) and post-*Policy* (2009 to 2016) timeframes. Points represent evenly spaced binned data that mimic the data's variance using spacing estimators, with a 95% confidence interval shown by the shaded area. Lines represent univariate *Policy* effects. Below each figure are univariate and multivariate estimates of the *Policy* effect and significance levels with clustered standard errors based on 'fire clusters'. # $P < 0.2$; * $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$.

Table 5. Effects of the *2009 Policy Guidance* (γ) on the management duration (Y_2) and area burned (Y_3) using a global sharp regression discontinuity (SRD) framework with covariates (i.e. multivariate models)

Policy effects for 'suppression' and 'other' fire samples are estimated with truncated negative binomial models, where the truncation point occurred at the value one less than the smallest value in management duration or area burned. The %Δ in the management duration (Y_2) and area burned (Y_3) of 'suppression' and 'other' fires are estimates of how the *2009 Policy Guidance* has affected these metrics for the average 'individual fire' from 2009 to 2016 compared with 2002 to 2008. Estimates of significance are calculated for two clustering methods: by 'fire cluster' to control for spatial heterogeneity, and by 'fire season' to control for temporal heterogeneity. Insignificant results should be interpreted as no detectable change regardless of the listed value. We used jack-knife simulations to evaluate the robustness of significant estimates with respect to space and time (superscripts in parentheses signify the number of replicates that failed to converge and were not included in jack-knife estimates of policy significance). Insignificance as assessed by jack-knife simulations lends evidence for a policy effect that was limited in space and/or time. Number of individual fires (n): Western US: Suppression = 5786, Other = 872; Inland Empire: Suppression = 1214, Other = 282; Rocky Mountains: Suppression = 547, Other = 102; Southwest: Suppression = 1105, Other = 271. * $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$

Response variable	'Suppression' fires				'Other' fires			
Regions	%Δ	Fire cluster	Fires season	Truncation point	%Δ	Fire cluster	Fires season	Truncation point
Management duration (Y_2)								
Western US	−7%			0	+36%	***(***^{1})	***(***^{1})	0
Inland Empire	+15%			0	+20%	*	*	1
Rocky Mountains	−16%			0	+49%	**(*)	**	4
Southwest	−8%			0	+62%	***(***)	***	0
Area burned (Y_3)								
Western US	+14%			40	+15%			40
Inland Empire	+74%			40	+7%			40
Rocky Mountains	+94%			40	+204%			40
Southwest	−20%			40	−7%			40

increase compared with 573 ha, the average-sized 'other' fire from 2002 to 2008. Likewise, with the exception of the local quadratic model with a 3-year bandwidth, our local models examining the total area burned by 'other' fires within 'fire years' detected a 429- to 473-ha increase (Fig. 7), which equates to a 499 to 550% increase compared with 86 ha, the average area burned by all 'other' fires within 'fire years' from 2002 to 2008. Additionally, global models detected a 144% increase in total area burned by fires being managed with 'other' strategies in receptive 'fire clusters' and 'seasons' (Table 4) and a 49% increase in the management duration of 'other' fires with robust effects across 'fire clusters' (Table 5).

Southwest In the Southwest, the only model to detect a change in the number of 'other' fires was a local linear model with a 6-year window that detected a potential 0.17 fire increase in 'other' fires per 'fire year' (Fig. 4), a 65% increase compared with the average of 0.26 'other' fires across 'fire years' from 2002 to 2008. Local models also detected an increase in 'other' fire management duration ranging from 11 to 19 days (Fig. 5). This equates to a 35 to 61% increase compared with 31 days, the average management duration of 'other' fires from 2002 to 2008. Likewise, global models detected a 62% increase in 'other' management duration with robust effects across 'fire clusters' (Table 5). The local linear models detected a 968- to 1028-ha increase in total area burned by 'other' fires within 'fire years' (Fig. 7), which equates to a 183 to 194% increase compared with 529 ha, the average area burned by all 'other' fires within 'fire years' from 2002 to 2008.

Odds ratios The practical implications of the *2009 Policy Guidance* are brought into focus when examining the *empirical* and *estimated* odds of a 'fire year' containing area burned by at least one 'other' fire (i.e. 'other'-to-'suppression' odds). We used data from 2002 to 2016 to calculate empirical 'other'-to-'suppression' odds for pre- and post-*Policy Guidance* time periods (2002–08 *v.* 2009–16). For example, during the pre-*Policy Guidance* period (2002–08), the western US had empirical 'other'-to-'suppression' odds of 1-to-8 (Table 6). This has the interpretation: for every 'fire year' that contained area burned by 'other' fire(s) only, there were 8 'fire years' that contained area burned by 'suppression' fire(s). In the post-*2009 Policy Guidance* period (2009–16), these odds changed such that for every 'fire year' that contained area burned by 'other' fire(s) only, there were 3.2 'fire years' that contained area burned by 'suppression' fire(s) (Table 6). When comparing empirical and estimated[1] post-*Policy Guidance* odds across the western US and each subregion, it revealed estimated effects of the *2009 Policy Guidance* that were just beyond the empirical increase in the isolated nature of 'other' fires (e.g. Table 6, 1-to-3.2 v. 1-to-3.1), where the gap represents additional constraints on the expanded use of 'other' strategies that are captured within our models. It is worth emphasising that empirical and estimated 'other'-to-'suppression' odds were very close. This suggests that much of the increased prevalence of 'other' fire(s) occurring in isolation within 'fire years' can be attributed to the *2009 Policy Guidance* and other concurrent advances (e.g. WFDSS).

[1]Estimated odds ratios were derived by applying the percentage change in the odds of a 'fire year' only containing area burned by 'other' fires that can be attributed to the *2009 Policy Guidance* (ZI model step, $Y_{4\,\text{'Suppression'}}$) to the empirical pre-*Policy Guidance* (2002–08) 'other'-to-'suppression' odds ratios. Note that 'suppression' ZI model steps estimate the odds of zeros, i.e. 'other' fires only.

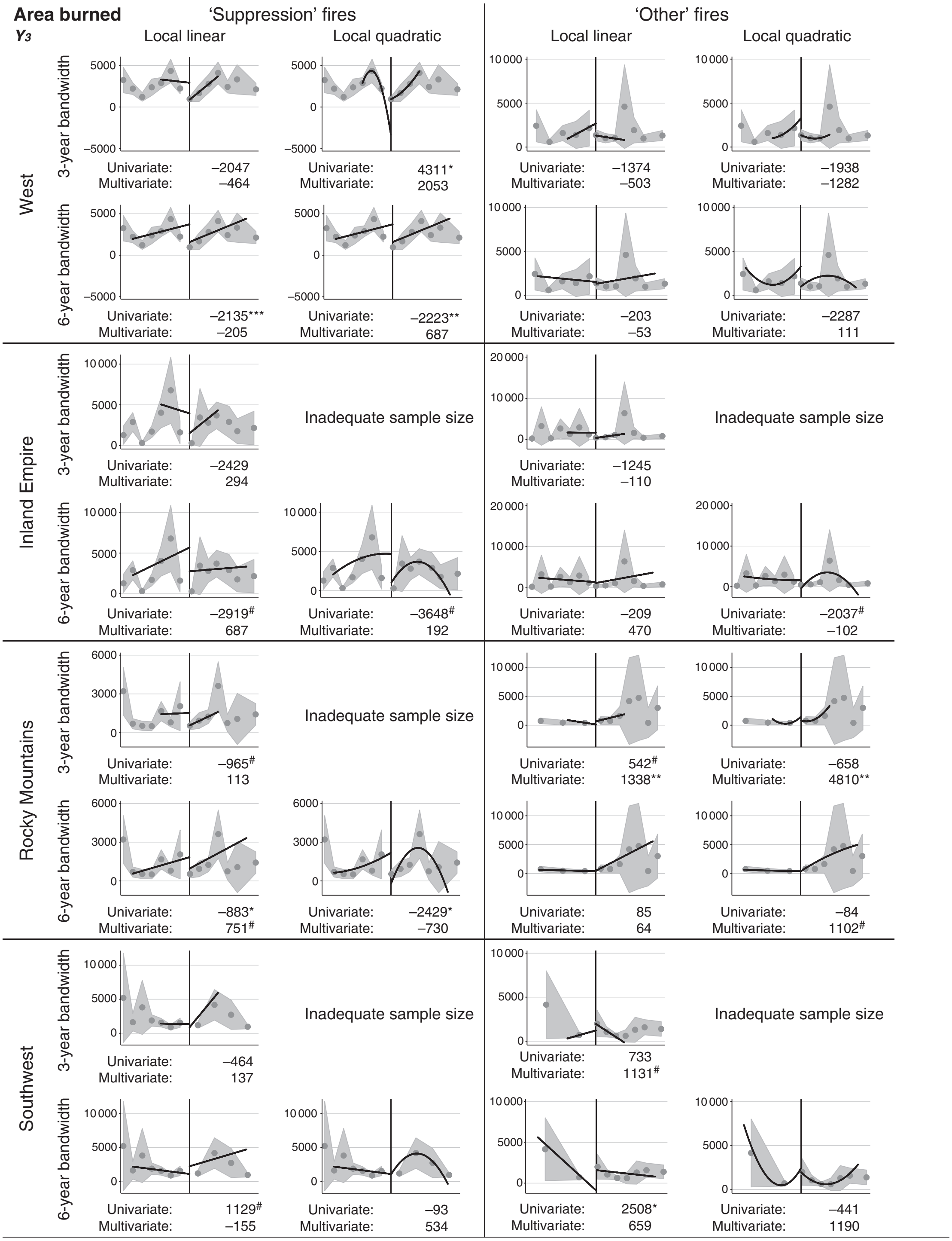

Fig. 6. Local sharp regression discontinuity (SRD) effects of the *2009 Policy Guidance* on area burned per fire (Y_3). The *y*-axis units are hectares. The vertical line within each plot separates pre-*Policy* (2002 to 2008) and post-*Policy* (2009 to 2016) timeframes. Points represent evenly spaced binned data that mimic the data's variance using spacing estimators, with a 95% confidence interval shown by the shaded area. Lines represent univariate *Policy* effects. Below each figure are univariate and multivariate estimates of the *Policy* effect and significance levels with clustered standard errors based on 'fire clusters'. $^{\#}P < 0.2$; $^{*}P < 0.1$; $^{**}P < 0.05$; $^{***}P < 0.01$.

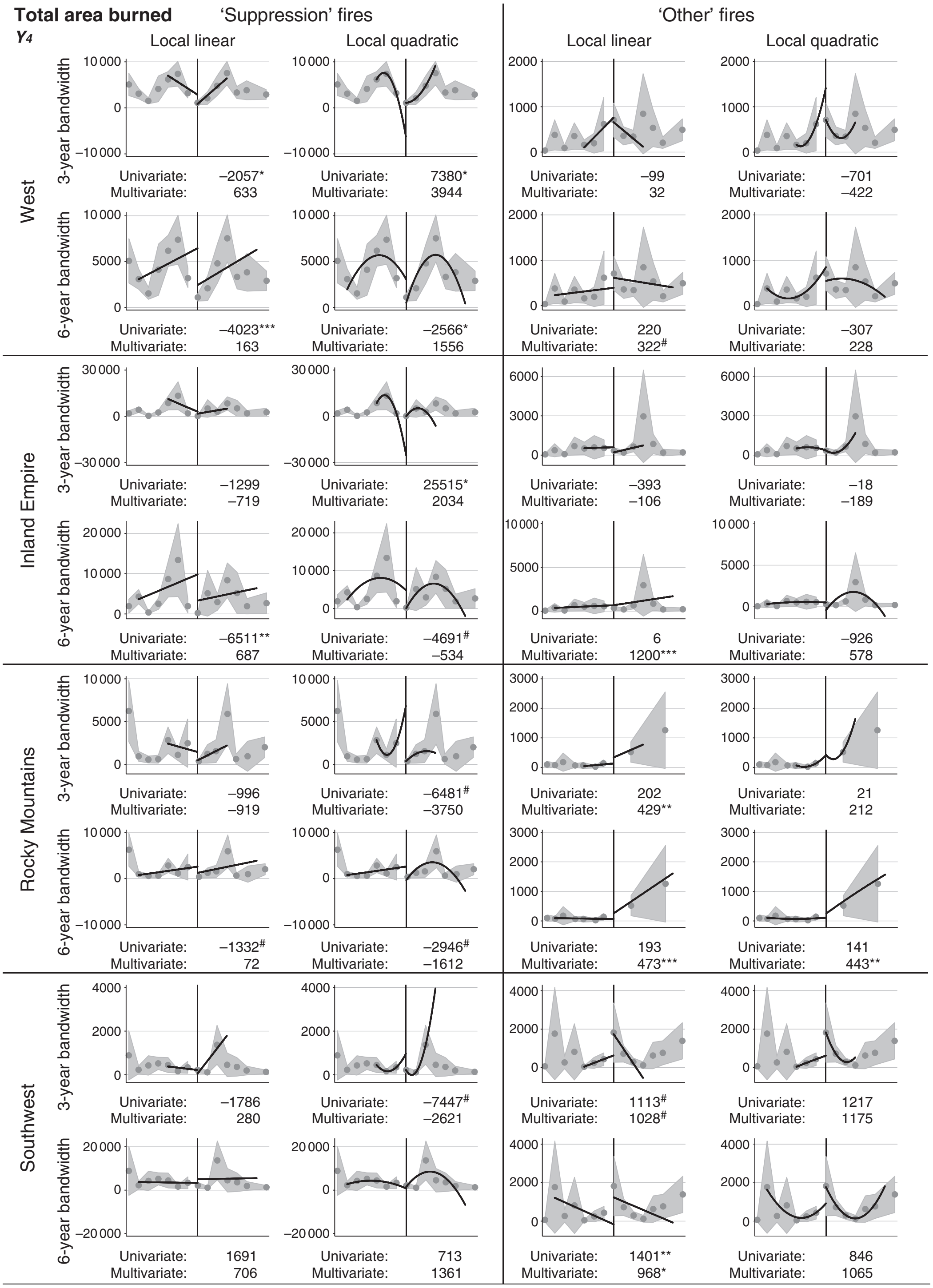

Fig. 7. Local sharp regression discontinuity (SRD) effects of the *2009 Policy Guidance* on total area burned per 'fire year' (Y_4). The *y* axis units are hectares. The vertical line within each plot separates pre-*Policy* (2002 to 2008) and post-*Policy* (2009 to 2016) timeframes. Points represent evenly spaced binned data that mimic the data's variance using spacing estimators, with a 95% confidence interval shown by the shaded area. Lines represent univariate *Policy* effects. Below each figure are univariate and multivariate estimates of the *Policy* effect and significance levels with clustered standard errors based on 'fire clusters'. $^{\#}$ $P < 0.2$; * $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$.

Table 6. Empirical and estimated 'other'-to-'suppression' odds ratios
Empirical odds for pre-*Policy Guidance* (2002 to 2008) and post-*Policy Guidance* (2009 to 2016) periods are reported. Estimated odds of post-*Policy Guidance* time periods are also reported. Odds are presented with 'other' strategies as a success

	Empirical 'other'-to-'suppression' odds				Estimated 'other'-to-'suppression' odds
	Pre-*Policy Guidance* 2002 to 2008		Post-*Policy Guidance* 2009 to 2016		Post-*Policy Guidance* 2009 to 2016
Total area burned (Y_4)					
Western US [A]†	1-to-8.0	<	1-to-3.2	<	1-to-3.1
Inland Empire	1-to-5.6	<	1-to-2.3	<	1-to-2.2
Rocky Mountains	1-to-6.1	<	1-to-2.2	<	1-to-1.8
Southwest	1-to-4.6	<	1-to-1.3	<	1-to-1.1

[A]The %Δ Odds from the 'Effect of *2009 Policy Guidance* on 'suppression' fires in Table B7 were applied to pre-*Policy Guidance* as follows. First, the odds ratio (OR) was derived from the western US model, Y_4 (OR = (156/100) + 1 = 2.56). Then the OR was applied to the empirical 'other'-to-'suppression' odds from 2002 to 2008 of 1-to-8.0 (pre-*Policy Guidance*). This resulted in estimated 'other'-to-'suppression' odds of 2.56-to-8.0, which were reduced to 1-to-3.1. Estimated ORs for total area burned by 'suppression' fires (Y_4): Western US, 2.56; Inland Empire, 2.58; Rocky Mountains, 3.44; Southwest, 4.07. †Interpretation: for every 'fire year' with area burned by 'other' fire(s) only in the pre-*Policy Guidance* time periods, there were 8 'fire years' that included 'suppression' fire(s) as well. During the post-*Policy Guidance* period, this changed to 1-to-3.2. If empirical pre-*Policy Guidance* < empirical post-*Policy Guidance* < estimated post-*Policy Guidance*, then additional constraints on the expanded use of 'other' strategies are captured within the model. This is represented by the gap between the empirical post-*Policy Guidance* and the estimated post-*Policy Guidance*.

Wildland fire and weather variables – SRD results

When examining global SRD models for the western US (Appendix B, Tables B3–B6, Supplementary material), several statistically significant fire and weather variables (denoted in capitals) controlled for seasonal effects and confounding variation (covariates in subregion models are not presented or discussed). Over the course of the fire season, the average 'suppression' fire duration had a declining positive association with the fire's DISCOVERY DATE (DD) (Table B4, +1% duration per unit increase in DD), until reaching a global maximum on 30 June (Table B4, note A), after which a negative association increased in strength with each passing day (Table B4, −0.004% duration per unit increase in DD × DD). The global maximum duration for 'other' fires occurred for those discovered on 1 June (Table B4, note B) with the North American monsoon traditionally beginning on 15 June with 50% of the annual precipitation occurring between July and September (Sheppard *et al.* 2002; Notaro *et al.* 2010). The global maximum number of 'other' fires occurred when there were 489 large FIRES (≥40.5 ha) in the western US (Table B3, note B), after which the number of 'other' fires over the course of a fire season began to decline.

Compared with a naturally ignited 'suppression' fire similar in all other aspects, a human-CAUSED fire burned for shorter durations (Table B4, −12%) and burned smaller areas (Table B5, −37%). As 'suppression' fires were managed for a longer duration and grew larger, the associated number of INJURIES and HOUSES AT RISK increased (Table B4, +7% duration per unit increase in INJURIES; +0.001% duration per unit increase in HOUSES AT RISK; Table B5, +38% area per unit increase in INJURIES; +0.02% area per unit increase in HOUSES AT RISK).

The zero inflated generalised linear model (GLM) steps suggest significant controls for confounding variation to be the fire's ignition CAUSE, the fire's REGION of origin and the aridity of the 'fire cluster' or 'season' of origin as captured in vapour pressure deficit (VPD). In the western US, an increase in VPD of 1230 Pa (approximately equal to a standard deviation; Table B1) significantly increased the odds of a fire's ignition location being in an arid 'fire cluster' or 'season' by 165% (Table B6, note B).

Other weather variables in our 'fire year' models ($Y_{1,4}$) capture important determinants of a fire manager's ability to use 'other' strategies to meet resource objectives. For example, changing ERC concurrent with a high AvgRH or changing PRECIPITATION during fire management within a 'fire year' were both positively associated with the number of 'other' fires (Table 7, +1.09% fires per unit increase in ERC; +7.35 to +17.91% fires per unit increase in PRECIPITATION). However, changing ERC concurrent with a low AvgRH during fire management within a 'fire year' was negatively associated with the number of 'other' fires (Table 7, −0.76% fires per unit increase in ERC).

When examining our individual fire models ($Y_{2,3}$), weather variables captured management intent and allocation of fire management resources relative to burning conditions, where a fire manager's desire and ability to suppress is: (1) complemented by fire weather; (2) at odds with fire weather; or (3) put aside because other fires or objectives take precedence. For example, in the western US, changing AvgRH concurrent with a low ERC during fire management was negatively associated with management duration (Table 8, −1.64% duration per unit increase in AvgRH) and area burned (−3.11% area per unit increase in AvgRH) for 'suppression' fires due to fire weather complementing suppression management. However, although changing WINDS concurrent with a lack of PRECIPITATION during fire management was also negatively associated with management duration for both 'suppression' (Table 8, −7.06% duration per unit increase in WIND) and 'other' fires (−5.92% duration per unit increase in WIND), a changing wind was positively associated with area burned for 'suppression' fires (+3.69% area per unit increase in WIND), highlighting the interplay between a manager's desire for quick containment, and the difficult nature of

Table 7. Effects of a per unit increase of weather metrics (α) on the number of fires (Y_1) and total area burned (Y_4) per 'fire year'-by-'fire year' classification

We used a zero inflated Poisson (ZIP) model when assessing weather effects on the number of 'other' fires, and zero inflated negative binomial (ZINB) models in other cases. Effects are presented as a percentage change per unit impact as assessed by incident response ratios (IRRs) and odds ratios [ORs]. Refer to Table 1 for weather metric units. 'Suppression' fire years = 3750; 'Other' fire years = 3750. Significance in number of fires (Y_1) and total area burned (Y_4) models are estimated with 779 wildland 'fire clusters' based on the origin of the weather data (i.e. RAWS). AvgRH – Low = 19%; AvgRH – High = 61%; ERC – Low = 3; ERC – High = 94; WIND – Low = 3; WIND – High = 13; PRECIPITATION – Low = 0; PRECIPITATION – High = 5. We based Low and High values on 5th and 95th percentiles. # $P < 0.2$; * $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$

Association of:	Conditioned on:	Number of fires (Y_1)		Total area burned (Y_4)	
		'Suppression' fires[A]	'Other' fires	'Suppression' fires	'Other' fires
ERC	AvgRH – Low	−0.08%	−0.76%**	−0.83%***	−0.93%
ERC	AvgRH – High	−0.57%***	+1.09%*	+0.12%	+1.74%**
AvgRH	ERC – Low	+0.09%	−1.56%**	−2.24%***	−3.65%**
AvgRH	ERC – High	−0.98%***	+2.50%#	−0.20%	+2.13%
PRECIPITATION	WIND – Low	−1.17%	+7.35%***	+15.07%***	+4.82%**
PRECIPITATION	WIND – High	+8.13%**	+17.91%***	+51.87%***	+18.43%***
WIND	PRECIPITATION – Low	+1.68%***	−11.74%***	+5.48%***	−0.37%
WIND	PRECIPITATION – High	+6.13%***	−7.72%***	+20.38%***	+5.60%
VPD		+0.01%***	−0.02%*	+0.02%***	<0.01%
		[−0.15%***]	[+0.20%***]	[−0.11%***]	[+0.08%***]

[A]Assessed with the removal of HOUSES AT RISK from the zero inflated model step for convergence.

Table 8. Effects of a per unit increase of weather metrics (α) on the management duration (Y_2) and area burned (Y_3) per fire-by-fire classification

We used truncated negative binomial models (refer to Table 5 for truncation points). Effects are presented as a percentage change per unit impact as assessed by incident response ratios (IRRs). Refer to Table 1 for weather metric units. 'Suppression' fires = 5786; 'Other' fires = 872. Significance in management duration (Y_2) and area burned (Y_3) models are estimated with 759 'suppression' and 262 'other' wildland 'fire clusters' based on the origin of the weather data (i.e. RAWS). AvgRH – Low = 17%; AvgRH – High = 60%; ERC – Low = 3; ERC – High = 97; WIND – Low = 2.5; WIND – High = 14.5; PRECIPITATION – Low = 0; PRECIPITATION – High = 3.3. We based Low and High values on 5th and 95th percentiles. * $P < 0.1$; ** $P < 0.05$; *** $P < 0.01$

Association of:	Conditioned on:	Management duration (Y_2)		Area burned (Y_3)	
		'Suppression' fires	'Other' fires	'Suppression' fires	'Other' fires
ERC	AvgRH – Low	<−0.01%	+0.14%	−0.77%***	−0.16%
ERC	AvgRH – High	+1.28%***	+0.14%	−0.31%	+0.87%
AvgRH	ERC – Low	−1.64%***	−0.36%	−3.11%***	−3.68%**
AvgRH	ERC – High	+1.12%***	−0.36%	−2.14%*	0.49%
PRECIPITATION	WIND – Low	+40.87%***	+7.31%***	+28.72%***	−4.79%
PRECIPITATION	WIND – High	+215.25%***	+36.98%**	+129.31%***	+34.07%**
WIND	PRECIPITATION – Low	−7.06%***	−5.92%***	+3.69%***	+1.80%
WIND	PRECIPITATION – High	+16.03%***	+0.63%	+21.57%**	+11.87%***
VPD		−0.02%***	−0.03%***	+0.01%*	<−0.01%

controlling many 'suppression' fires despite resource application. Uniquely, changing PRECIPITATION concurrent with calm WINDS and changing AvgRH concurrent with a high ERC were both positively associated with management duration for 'suppression' fires (Table 8, +40.87% duration per unit increase in PRECIPITATION; +1.12% duration per unit increase in AvgRH), because there is less need to quickly control a fire that is unlikely to spread (−2.14% area per unit increase in AvgRH), or when other fires or objectives take precedence (+28.72% area per unit increase in PRECIPITATION).

An extended examination of other weather results can be found in Appendix A4. The parametric coefficients and statistical significance of each fire and weather variable for the global western US model can be found in Appendix B, Tables B3–B6. Results for zero inflated model steps can be found in Table B7 (Supplementary material).

Discussion

Number and area burned

Our investigation of 9238 fires from 2002 to 2016, inclusive of federal and state management, provides insight into changing wildland fire management in the western US, with evidence pointing towards the *2009 Policy Guidance* and other fire management advances (e.g. WFDSS) having a meaningful effect. 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, (Table 3; Fig. 1), which increased to 61 and 19% from 2009 to 2016. We also found robust evidence of an increase in the number of large ‘other’ fires (Fig. 4), with our global models revealing this effect to be concentrated within receptive ‘fire clusters’ (Table 4). 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% *v*. 19% in the western US). California, however, continued the application of ‘suppression’ strategies on most large fires ($\geq$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. 4), we only found limited evidence of an increase in total area burned by ‘other’ fires annually in the Inland Empire (Fig. 7), and modest evidence of an increase in area burned by ‘other’ fires individually and in total in the Rocky Mountains (Figs. 6 and 7). 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’ (Figs. 4 and 7). 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 odds of a ‘fire year’ only containing ‘other’ fire(s) (Table 6). In other words, more areas experienced ‘other’ fire(s) only over the course of a fire season.

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.* 2017*b*; Kelley 2017). Arguably, the most important barrier remains the high accumulation of fuels at the stand level, and the continuity of such 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 ($\sim$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 (e.g. Table 7 $-$11.74% ‘other’ fires per unit increase in WIND), 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 (Table 8, $-$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 (Table 8, +7.31 to +36.98% duration per unit increase in PRECIPITATION) 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 (Table 8, +28.72% area burned per unit increase in PRECIPITATION), 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 (Table 7, +15.07 and +4.82% area per unit increase in PRECIPITATION), suggesting a greater willingness to allow fires to play a natural role during docile weather conditions that support lower burn severity 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.* 2015), 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 severity 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-severity wildland fires that are managed for resource objectives with strategies other than full suppression. Overall, to expand the use of 'other' strategies to maintain forest restoration 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).

Variability across space and time

Despite the flexibility afforded by the *2009 Policy Guidance*, the widespread application of 'other' management strategies is still limited by numerous barriers as discussed above. Interacting with each of these are complex interannual lags in resource availability that are manifest when examining the fire history of the western US, in terms of the number of fires and area burned (Fig. 1). For example, when examining docile 'fire years', there were more 'other' fires in 2009 than in 2010, even though there were fewer fires in 2010 overall, which would suggest a greater share of resources in 2010 could have been contributed to 'other' strategies to meet resource objectives. Rather, 'suppression' fires in 2010 burned more area at the median (Fig. 8, ~220 ha in 2009 compared with ~300 ha) and as a percentage of total area burned annually (Fig. 1, 61% in 2009 compared with 86% in 2010). Factors leading to the increased use of 'suppression' strategies from 2009 to 2010 may include fewer available resources and personnel needed to use 'other' strategies for extended durations. To increase the use of 'other' strategies, land-management agencies will need to prioritise opportunities to reintroduce fire and increase experience with 'other' strategies, which may include strengthening local resources during docile fire years and shoulder seasons.

Other interannual patterns reveal potential lost opportunities to increase the median size of 'other' fires (Fig. 8). For example, the median size of 'other' fires was at a local minimum during the active fire year of 2007 (Fig. 1). From here, the median size of 'other' fires steadily increased until reaching a local maximum in 2012 (Fig. 8), another active fire year (Fig. 1). Then, when western-wide fire activity began to decline in 2013, the median size of 'other' fires counterintuitively dropped to a new local minimum, despite 2013 being favourable to the use of 'other' strategies. Whereas docile weather conditions appear to result in

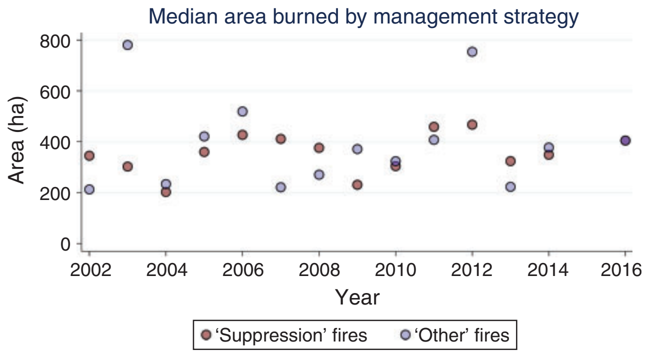

Fig. 8. Median area burned by management strategy for large 'suppression' and 'other' fires (≥40.5 ha) in the western US.

more 'other' fires with greater area burned as discussed in *Weather and seasonality* above, favourable climatic years with lower fire frequencies provide opportunities to reintroduce fire to the landscape, which data suggest may not be fully leveraged. As climate conditions continue to change across the western US, it will be increasingly important to take advantage of favourable climate patterns to expand fire weather windows and increase the area burned with a minimal risk of unintended high-severity fires. Such opportunities may be limited given current climate projections, so there is a certain amount of urgency to reduce fuels and create resilient landscapes.

Interannual patterns in the use of 'other' strategies could also be affected by political and economic pressures surrounding social-ecological issues. For example, the 2000 Cerro Grande Fire of New Mexico began as a prescribed fire, but then escaped, causing extensive negative effects (Lavine *et al.* 2006; Kokaly *et al.* 2007). The fallout from this and other examples (e.g. 2012 Lower North Fork Fire in Colorado) highlight the potential risks of using fires to meet resource objectives (Miller and Aplet 2016) and the risky behaviour such events may foster. In other instances, the use of 'other' strategies has been limited to minimise costs. For example, in May 2012, a directive from a deputy chief at the US Forest Service emphasised a 'suppression' approach to all fires to limit costs during the upcoming active fire season unless otherwise approved by the Regional Forester (Hubbard 2012). There is a high likelihood this decreased the number of 'other' fires in 2012 (with the notable exception of the Inland Empire; Fig. 2) and may have had a lagging effect during the 2013 fire season. Though more research is needed to disentangle political and economic pressures surrounding social-ecological effects, these examples highlight the risk-averse nature within many agencies directed to increase the use of fire as a restoration tool. At the same time, since the *2009 Policy Guidance*, many regions have adopted incentive systems where local units are evaluated based on their ability to reach a certain target of accomplished activities (USDA 2018*a*). In many cases, all or portions of lightning-ignited 'other' fires are used to meet these targets, thereby providing a significant incentive to use 'other' management strategies when possible. For example, in the Southwest, such fires accounted for more than half of the area burned in 2017 and 2018 (Lynch and Evans 2018, 2019).

Conclusions

Our analyses of federal and state fire management revealed that the *2009 Policy Guidance* along with other concurrent advances in fire management since 2009 have led to a significant shift in the use of fire management strategies. Most striking is the widespread increase in the odds of fire managers using strategies other than full suppression when circumstances allow (Table 6). Some regions also experienced an increase in the number and management duration of 'other' fires (Figs. 4 and 5) that have resulted in a limited increase in size and annual area burned (Figs. 6 and 7). In part, these limits are due to 'other' fires being largely confined to docile weather conditions in the fall shoulder season. Increasing 'other' fire area will require greater risk acceptance in allowing naturally ignited fires to burn outside the current safe window including in the spring and throughout favourable climate years. These steps will create the heterogeneity needed to reduce the increasing trend of larger and more severe fires.

To strengthen any commitment to reintroducing fire to the landscape, future qualitative research on diverging regional results and the distribution of fire management strategies will likely uncover important environmental and social drivers of fire management decisions at the local and regional level, complementing our quantitative analyses. Other avenues for future research include extending our analyses to recent and future years, and using our SRD framework to guide the future expansion of 'other' strategies across the western US (e.g. Young *et al.* 2018). Because fire policy, public perception and fire management continue to evolve, it is also important to track the changing distributions of fires and management strategies. As the use of 'other' response strategies increase, managers and policy-makers will need clear documentation of trends and the effects on forest health, resource objectives and human communities in order to maintain institutional and public support.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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