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Research article

Multiple social and environmental factors affect wildland fire response of full or less-than-full suppression

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ABSTRACT

Wildland fire incident commanders make wildfire response decisions within an increasingly complex socio-environmental context. Threats to human safety and property, along with public pressures and agency cultures, often lead commanders to emphasize full suppression. However, commanders may use less-than-full suppression to enhance responder safety, reduce firefighting costs, and encourage beneficial effects of fire. This study asks: what management, socioeconomic, environmental, and fire behavior characteristics are associated with full suppression and the less-than-full suppression methods of point-zone protection, confinement/containment, and maintain/monitor? We analyzed incident report data from 374 wildfires in the United States northern Rocky Mountains between 2008 and 2013. Regression models showed that full suppression was most strongly associated with higher housing density and earlier dates in the calendar year, along with non-federal land jurisdiction, regional and national incident management teams, human-caused ignitions, low fire-growth potential, and greater fire size. Interviews with commanders provided decision-making context for these regression results. Future efforts to encourage less-than-full suppression should address the complex management context, in addition to the biophysical context, of fire response.

1. Introduction

Wildfire incident commanders make suppression decisions in increasingly challenging social and environmental contexts (Gude et al., 2008; Essen et al., 2022; Miller et al., 2022). Increased housing development, frequent hot droughts, and public expectations lead to demand for increased fire suppression and expanding firefighting costs (Bowman et al., 2011; Canton-Thompson et al., 2008; Ingalsbee and Raja, 2015; Radeloff et al., 2018; Thompson et al., 2000). Simultaneously, incident commanders are asked to allow rather than suppress fire, when appropriate (Houtman et al., 2013; Kauffman, 2004; National Academy of Sciences and Medicine, 2017). Allowing fires to burn can have beneficial effects such as reducing fuel loads, promoting fire-adapted species, reducing firefighting costs, and protecting fire responders (Donovan and Brown, 2005; Pausas and Keeley, 2019). Changing suppression method choices for unplanned ignitions is a 'largely untapped but important, if not essential, opportunity to restore landscape conditions and reduce future risk' (Thompson et al., 2018). However, incident commanders face barriers to choosing less-than-full suppression (Gebert and Black, 2012), raising questions about the conditions under which managers have selected less-than-full suppression.

In many countries, decisions about full suppression are made within a unified Incident Command System (ICS) that integrates disaster policies, personnel, facilities, equipment, communications, and consistent documentation of decisions (Calkin et al., 2014; Hannestad, 2005). In the United States (US), suppression choices are made primarily by landowners and land managers, with input and implementation within the ICS by incident commanders and incident management teams (hereafter 'commanders' and 'teams', respectively). Commanders and teams can change during a fire, typically progressing from a local to

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regional or national level and then reversing as fire activity decreases. Regional or national teams are generally assigned or requested when fires are growing rapidly and risks are high. Fire management involves national and local fire policies, plans, and agreements, which complicate wildland fire management and increase goal ambiguity (Buck et al., 2006; Jensen, 2006; Schultz et al., 2019; Stephens and Ruth, 2005). This complex system must be navigated by commanders and teams as they select a suppression method appropriate to their conditions (Buck et al., 2006).

Suppression methods include full suppression, point-zone protection, confinement/containment, and maintain/monitor. Full suppression 'implies a strategy to 'put the fire out,' as efficiently and effectively as possible, while providing for firefighter and public safety' (NIFC, 2011). Full suppression attempts to limit fire spread and potentially severity, while increasing resources used during active fire management. Confinement/containment is a strategy that uses natural and constructed barriers to restrict fire to a defined area (NIFC, 2011). When using point-zone protection, teams protect specific locations from fire without lining the fire's full edge (NIFC, 2011). Maintain/monitor is the process of observing the fire and recording data collected (NIFC, 2011).

These suppression decisions are communicated through fire incident reports that provide critical information for fire management within the ICS. In the US, commanders report fire suppression methods in ICS incident status summary reports called "209s", which provide a consistent record of suppression methods. The 209s are publicly available, daily status reports in which the commander records information about the fire and its context, including weather and fire behavior outlook, resource status, and suppression method. Completed 209s help regional coordinators assign firefighting resources across the country (St. Denis et al., 2020).

This study examined conditions that impact suppression method decisions in the US northern Rocky Mountains, an ideal region for study given its fire-adapted ecosystems and landscapes from remote wilderness to expanding wildland-urban interface (WUI) (Radeloff et al., 2018; Westerling, 2016). Specifically, we asked what management, socioeconomic, environmental, and fire characteristics were associated with full suppression, point-zone protection, confinement/containment, and maintain/monitor suppression methods reported during fire incident reports in the US northern Rocky Mountains between 2008 and 2013? We used both quantitative and qualitative methods to illuminate the context for decisions during fire incidents.

Many management, socioeconomic, environmental, and fire behavior variables impact the choice of suppression method (Table 1) (Thompson, 2014). We expected suppression decisions to be associated with socioeconomic factors such as housing density, WUI development, home values, and distance to roads and railroads (Cardille et al., 2001; Gude et al., 2013). We hypothesized that fires on public land and wilderness or wilderness-study areas are more likely to be managed with less-than-full suppression, based on previous studies (Bar-Massada et al., 2014; Radeloff et al., 2018). The WUI exacerbates risks and effects of fire to human life and structures (Kramer et al., 2019; Radeloff et al., 2018), likely leading to more aggressive suppression (Cardille et al., 2001). Areas with higher median home values may receive more aggressive fire suppression, because wealthier residents have greater political power, agency responsiveness, or more favorable financial cost-benefit analyses (Anderson et al., 2020). Alternatively, suppression choices could be

Table 1
Variable descriptions and hypotheses.

Independent Variable	Hypotheses; full suppression associated with:	Description (units)	Mean	Range
Management Variables				
Report Date	Earlier report date	Date of report; given per day of incident out of 365 (Julian day)	241.9	73–363
National Preparedness Level	Higher National Preparedness Level	National Preparedness Level per day of incident; lowest (1) - highest (5)	2.9	1–5
Team Type	Higher level (more national) IMTs/ICs	Ranking of incident commander or team, based on position training requirements and incident complexity; national (1) - local (7)	4.1	1–7
Ownership State	Montana in comparison with other states	State in which the fire occurred (Montana is the reference condition)	1.9	1–4
Unit Type	Non-federal land	Type of unit managing the fire or serving as lead agency; non-federal (state, interagency, or county/local) (0) or federal (1)	0.9	0–1
Perceived Growth Potential	Higher fire growth potential	Predicted future fire growth estimated by officer completing the 209; low (1) to extreme (5)	2.5	1–5
Socioeconomic Variables				
Median Home Values	Higher median home values	Median home value within 5 km surrounding fire's point of origin ($US 2010)	5.4	1–11
WUI Flag	WUI flags (1 or 2)	Indicator that identifies the area within 5 km surrounding fire's point of origin as intermix (1), interface (2), or neither (0)	0.1	0–2
Seasonal Housing Unit Density	Higher seasonal housing density	Seasonal housing unit density per square kilometer within fire kilometers surrounding fire's point of origin (housing units/km2)	1.7	0–111.8
Housing Unit Density	Higher total housing density	Housing unit density per square kilometer for the 5 km surrounding fire's point of origin (housing units/km2)	5.9	0–766.4
Distance to Road/Rail	Higher proximity to roads/ railroads	Distance to nearest road or railroad from the fire's point of origin (km)	194.3	1–375
Environmental and Fire Behavior Variables				
Area	Higher fire size	Area reported in 209 (converted to km^2)	72.5	1–160
Incident duration	Shorter fire duration	Duration of the incident, determined by the final report DOY and the start DOY in the 209 (days)	22.8	0–164
Cause	Human-caused ignitions	The cause of the fire: lightning (1), unknown or under investigation (2) and human (3)	1.3	1–4
Primary fuel model	Lower primary fuel model	Primary fuel model for landscape (Grass = 1–3, Shrub = 4–7, Timber Litter = 8–10, Logging Slash = 11–13; levels within each)	3.8	1–13
Vegetation density	Lower vegetation density	Vegetation density (%)	84.2	4.8–100
Aspect	North-facing slopes	Mean aspect of the land within 5 km of the fire point of origin: east (1), southeast (2), south (3), southwest (4)	3.0	1–4
Terrain	Low to moderate terrain	Description of terrain, from low to extreme; includes steepness, difficulty to navigate	3.4	1–5
Elevation	Lower elevation	Elevation at point of origin (m)	1973.2	296.6–3292.1
Temperature	Higher temperatures	Temperature (^{o}C)	24.0	−15.0–43.89
Relative Humidity	Decreased relative humidity	Percent humidity (%)	127.2	1–241
Latitude	Control variable	Coordinates based on fire point of origin	45.5	42.44–48.98
Longitude	Control variable	Coordinates based on fire point of origin	−113.5	−119.3–104.1

independent of whether houses are expensive or inexpensive (Gude et al., 2013). Fires closer to roads and railways are easier for firefighters to access and may threaten transportation routes, leading to more frequent full suppression implementation (Narayanaraj and Wimberly, 2011).

Environmental and fire behavior characteristics drive fire decision-making. Commanders are more likely to choose full suppression when current and projected weather conditions are conducive to high fire spread (warmer temperatures, lower humidity, dry fuels, and wind). Lower elevation, low to moderate terrain roughness, and lower vegetation density are expected to enable more aggressive suppression activity on the ground. Larger, longer fires pose greater obligation to teams, as do unpredictable human-caused ignitions (Syphard and Keeley, 2015).

Policy, administration, and norms also influence decisions to suppress or allow fires (Jensen, 2006; Stephens and Ruth, 2005). When fewer firefighting resources are available, full suppression may not be an option (Hand et al., 2017). US fire policies and legislation do not sufficiently incorporate fire ecology science, reducing decision space for commanders (Ingalsbee, 2017). This has been changing in some respects. The National Strategy identified the US northern Rocky Mountains as a priority area for fuels management and community planning and coordination, signaling a need for reduced use of full suppression and increased use of prescribed burns, as well as managing fires for resource use or ecological benefit (US Department of Interior and US Department of Agriculture, 2014).

We hypothesized that full suppression is more likely with regional or national teams than local teams. Regional or national teams are usually requested when perceived risk to people or resources is high and local resources are insufficient. We expected federal public land managers to be more likely than state public land managers to allow fire, as the US Forest Service (USFS) allows for less-than-full suppression where appropriate - particularly in wilderness areas.

The timing of fires within the fire season may also drive suppression decisions (Stonesifer et al., 2017). We hypothesized that full suppression is more likely earlier in the fire season when resource availability is high and fire weather is more moderate. Alternatively, high National Preparedness Level (NPL) indicates extreme fire weather and limited resources, and we expect higher NPL to be associated with a greater likelihood of full suppression (Dunn et al., 2017).

2. Methodology

2.1. Study area

The US northern Rocky Mountains is a relatively sparsely populated, high-elevation region comprised substantially of public land with rapidly growing rural residential development and urban centers. The region includes northeast Washington, northern majority of Idaho, western Montana, and northwestern Wyoming in US Environmental Protection Agency Ecoregions 15, 16, 17, and 41 (Fig. 1) (Harvey et al., 2016). Forests or woodlands cover 74% of the landscape (Harvey et al., 2016), and conifers dominate the forests. Gradients in elevation and moisture drive variation in forest type and fire regime (Baker, 2009). Higher elevation, cooler and wetter subalpine forests (45% of forests) historically experienced infrequent, high-severity fires, whereas warmer, mid-montane forests (53% of forests) burned at mixed severities and frequencies (Baker, 2009; Harvey et al., 2016; Schoennagel et al., 2004). At lower elevations, where climate is typically warmer and drier, frequent and low-severity fires historically maintained relatively open forests (Arno, 1976). The region has a late fire season relative to other US regions and struggles to obtain firefighting resources when more populated regions have active fire seasons (Hand et al., 2017).

Public lands account for 85% of the study area. Of public lands, USFS manages 77%, Bureau of Land Management (BLM) manages 6%, and Bureau of Indian Affairs (BIA) and National Park Service (NPS) each manage 4%. US Army Corps of Engineers, US Fish and Wildlife Service, state agencies, and non-governmental organizations manage the remaining 9% of public land. Wilderness or wilderness study areas account for 11% of public land (9% of the overall study area).

2.2. Mixed methods research design

We developed an iterative mixed methods research approach to combine qualitative and quantitative data. Mixed methods research incorporates complementary techniques that account for weaknesses in qualitative and quantitative methods, such as generating and testing hypotheses and resolving complex results by providing context (Creswell and Clark, 2017; Greene et al., 1989; Johnson and Turner, 2003). Our iterative phases were 1) key informant interviews, 2) a draft regression model, 3) interviews with commanders, 4) final regression model, and 5) pairing regression variables with interview quotes.

2.3. Data sources

2.3.1. 209 Reports and fire incident selection

The 209s reported through and collected by USFS from 2008 to 2013, provided by Karen Short at USFS, were used as the data source for this study. The study was limited to 2008–2013 due to changes in reporting categories before 2008 and availability at the time of our analysis of digital reports after 2013. The frequency and extent of completion of 209s during fire incidents depends on fire size and complexity, team type, resources committed, and suppression action intensity (Hannestad, 2005).

Of the 10,049 209s from incidents occurring during the study period, we identified 4751 209s from incidents with points of origin in our study region that reached fire sizes $\geq$40.5 ha and had a suppression method reported. The size requirement removed most prescribed fires unless prescribed burns became wildland fire incidents. Decisions made on the initial day of the incident tend to establish fire suppression strategy for the duration of the incident. Most incidents remained within several kilometers of their point of origin (mean radius of ultimate fire size = 5.1 km).

2.3.2. Dependent variable

The dependent variable was the suppression method from each fire incident report, categorized as binomial and ordinal. The binomial analysis compared less-than-full suppression (0) with full suppression (1). The ordinal analysis treated suppression method as an ordered categorical variable: maintain/monitor (1), point-zone protection (2), confinement/containment (3), and full suppression (4). Suppression methods were ordered based on their definitions and interviews with key informants and commanders.

2.3.3. Independent variables

Independent variables were compiled from 209s and available geospatial data (Table 1, sources in Table S1). The 209 data provided report day of the year, team type, terrain, and unit type in which the incident occurred. Incident duration, fire size, unit type, and team type were created from variables in the 209s. NPL is established by the National Multi-Agency Coordination Group, depending on fuel and weather conditions, resource availability, and fire activity. Independent variables extracted from spatial sources include elevation, aspect, weather, distance to road/railroad, vegetation density, housing density, and WUI flags. These were spatially joined to incidents in ArcMap 10.5.1 based on fire points of origin (ESRI, 2011).

Weather information was inconsistent and incomplete in 209s due to multiple factors such as limited time and resources for reporting from the field, so external weather data from PRISM was added, joined to each fire incident based on the closest weather tower (Table S1). However, in some cases, the closest tower to a fire incident was up to 15 km away, could be at an entirely different elevation, and might only report

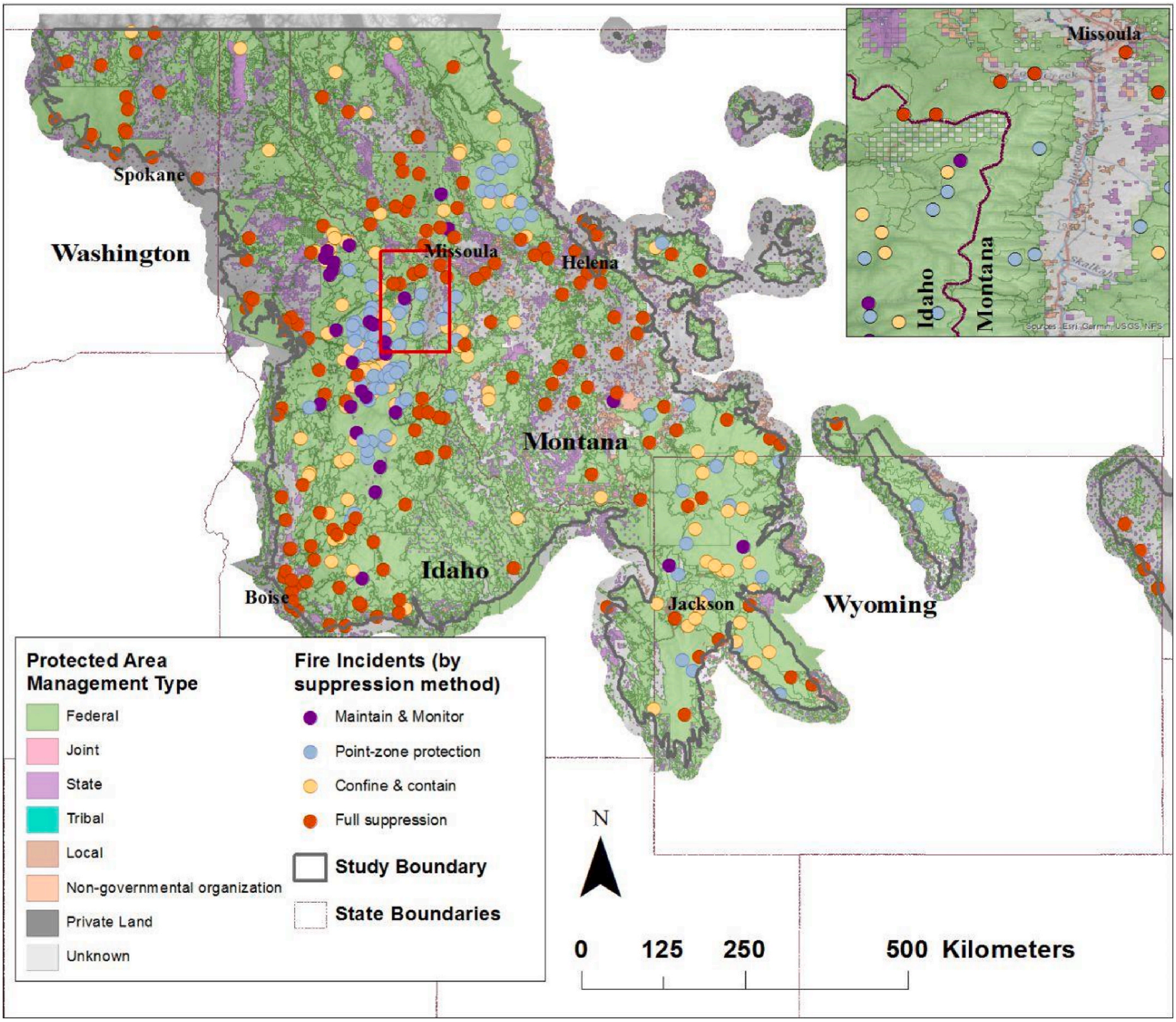

Fig. 1. Map of the study area including fire incidents with ultimate fire size of 40.5 ha or more.

information such as wind speed once per day. We compared PRISM weather tower data with weather data reported in 209s and a *t*-test showed they were not correlated. Therefore, weather was excluded from analyses.

2.4. Statistical analysis

To avoid collinearity among predictors (here, defined as Pearson's r $\geq$ 0.45), we removed state, terrain, and WUI flag from both models (Table S2). We used generalized additive mixed models (GAMMs) using the R package 'mgcv' to determine which factors impacted suppression method decisions (Wood, 2017). GAMMs allow for both binomial and ordinal response variables and mixed effects to address spatial and temporal autocorrelation. Longitude and latitude were added to regression models via splining to account for spatial dependence, avoiding violation of the assumption of spatially independent residuals. A random identification number was assigned to the daily observations ($n = 4751$) and added to regression models as a random effect, assigning an identity penalty, also known as a ridge penalty (Wood, 2008).

We fit separate GAMMs for binomial and ordinal responses and identified the best model based on AIC. In addition, we fit separate binomial models for fires that started on federal lands. All analyses were performed in R (R Core Team, 2018). The final set of 15 predictors for the binomial and ordinal models include: report date, NPL, team type, perceived growth potential, unit type, seasonal housing unit density, housing unit density, median home value, cause of ignition, fire area, aspect, primary fuel model, vegetation density, distance to road/railroad, and incident duration. Odds ratios (reported in the supplementary material) greater than 1 indicate the size of a positive effect and odds ratios closer to 0 indicate the size of a negative effect.

2.5. Interviews

We conducted eleven interviews to provide context for our quantitative analysis of suppression method choices. Three initial key informant interviews included a commander, a USFS fire management officer, and Nature Conservancy controlled-burn boss, all with over ten years' experience in incident management teams. The eight commanders selected for interviews were commanders from fires during which the reported suppression method changed, indicating a decision made and/or implemented by the commander, which narrowed the potential interviewees. From eighty-two commanders listed on the two days before, day of, and two days after suppression method change, we reached out to twenty-three whose contact information could be found online and interviewed the eight who responded. Of those interviewed, seven still worked in the study area at federal and state agencies or as consultants in fire management. Interviews were conducted between June and September 2019 via phone, recorded, and manually transcribed. We combined deductive or top-down coding and inductive or bottom-up coding to identify commander perspectives on each variable and inform our hypotheses (Boeije, 2009). The first author manually coded the transcripts and consulted with an additional researcher to validate the coding. We selected quotes that explain each variable's impacts on suppression method choice or provide context for the importance of the variable. In this way, evidence from interviews and regression models can strengthen or challenge interpretations of statistical relationships. Interviewees did not generate any additional quantitative variables for the regression model beyond those identified in the literature review.

3. Results

From 2008 to 2013, commanders completed reports for 374 incidents in the study boundary on 4751 days. Of the 335 incidents (90%) that did not have a change in suppression, 47% reported full suppression, 27% reported confinement/containment, 19% reported point-zone protection, and 7% reported maintain/monitor. Of the daily reports, 42% reported full suppression, 27% reported confinement/containment, 22% reported point-zone protection, and 8% reported maintain/monitor. Of the 39 incidents (10%) that had a change in suppression, the most common changes were between confinement/containment and point-zone protection and between full suppression and point-zone protection.

3.1. Factors affecting suppression method decisions

Full suppression was associated with higher housing density, earlier days in the year, regional or national teams, non-federal land jurisdiction, human-caused ignitions, low fire-growth potential, and greater fire size. (Table 2, Fig. 2). Both models resulted in similar outcomes, but in the ordinal model, fire management was less aggressive when NPL and median home value were high.

Management variables such as team type and unit type were strongly associated with suppression method. National and regional teams were more likely to suppress fires than local teams. National or regional teams rely more on tactics associated with their 'home' topography, whereas local northern Rocky Mountains teams are better equipped for flexible suppression strategies according to interviewees. Federal lead agencies were less likely to employ full suppression methods, compared to fires with a state, interagency, or local lead agency.

Among the regional socioeconomic variables, housing density was most strongly associated with suppression method. Full suppression was most likely in areas of higher housing density, which was confirmed by interviewees as a driving motivation for increased suppression. Odds ratios reveal that housing density had the largest impact on suppression method of all the variables in the model (Table S4). In the ordinal model, full suppression was less likely in areas with more expensive homes, which contradicted our hypothesis and the interviewee quote. Distance to road or railroad was not significantly associated with suppression methods, although the interviewees expressed the importance of roads in fire suppression tactics.

Environmental and fire behavior variables were associated with different suppression method choices. Full suppression was more likely for incidents with lower fire growth potential, higher density vegetation, and larger fire sizes. Fires with full suppression had shorter incident durations. Vegetation density and fire size were positively associated with increased suppression.

In the models that examined only the fires that started on federal land, wilderness areas were strongly associated with less-than-full suppression (Table S5). The federal-only models were consistent with the overall models, except distance to road and railroad was significantly associated with full suppression in the binomial model, human-caused ignitions were significant in both models, and housing unit density was not significant in either model.

Relationships among some variables shifted during the fire season. Local teams chose less aggressive suppression strategies than national teams, but later in the year, less aggressive suppression methods were implemented across all team types (Fig. 3). At higher housing densities earlier in the year, full suppression was more likely, but later in the year, all suppression methods had similar likelihoods (Fig. 4).

3.2. Qualitative perspectives on model variables

Interviewees' perceptions of fire decision-making were generally consistent with regression results. Commanders' quotes explain how and why variables in the model may be associated with suppression methods (Table 2). Commanders particularly emphasized the importance of housing density, jurisdiction, cause of ignition, report date, terrain, team type, NPL, and fuels. Reporting full suppression was viewed as increasing public support and decreasing decision-maker liability, even if the team did not have the capacity or intent to suppress the full perimeter. Commanders also felt a lack of opportunity to report and receive credit for the value and risk of less-than-full suppression within the agency. In talking about less-than-full-suppression approaches, one interviewee said:

> It's the right thing to do on the landscape collectively, but there's no way to positively report that. I did the right thing by not putting this fire out. I should get a pat on the back. If we could recognize the work and risk that it takes to do that … I think we would have a) better alignment in organization and funding and b) we would have line officers who are more willing to make those decisions on game day.

4. Discussion

This research highlights the importance of management and socioeconomic variables in fire suppression method decisions in addition to well-explored environmental and fire characteristics (Birch et al., 2015; Holsinger et al., 2016; Essen et al., 2022). The US northern Rocky Mountains is a high-elevation, relatively sparsely populated region comprised largely of public land. However, significant WUI development is growing in the region, reflective of many rural and semi-rural communities globally (Radeloff et al., 2018; Chas-Amil et al., 2013). Fires are allowed to burn in this region more often than other regions due to the remoteness and proportion of federal land, yet among fires that required 209 reporting from 2008 to 2013 in the final dataset, nearly half were managed as full suppression and another quarter as confinement/containment.

4.1. Multiple factors influence suppression decisions

Our hypotheses about factors that influence suppression methods were generally supported (Tables 1 and 2). As expected, full suppression was less likely on public land, mostly in wilderness areas, and when housing density was lower and distance to roads was higher, in line with previous studies (Bar-Massada et al., 2014; Radeloff et al., 2018). The models and interviews supported our hypothesis that full suppression was more likely earlier in the fire season, with shorter incident durations, and with human-caused ignitions (Fig. 4, Table S3).

Federal public land managers were more likely than state managers to implement less-than-full suppression. As the National Strategy continues to advocate for flexible incident management, we may see more

Table 2
Model coefficients and associated interview responses.

Independent Variable	Binomial, Standardized Estimate (FS = 1, NFS = 0)	Ordinal, Standardized Estimate (FS = 4, CC = 3, PZ = 2, MM = 1)	Interview quote that provides context for each factor that impacts suppression method (bold added for emphasis)
Management Variables			
National Preparedness Level	−0.015	−0.141***	'**If you're at a PL 5, that means multiple regions are going at once, so as far as getting resources to implement your plan and get in and deal with a larger fire, it gets real difficult. That is definitely a driver. We end up putting out some fires that in other years, we would manage on the landscape** but there just wasn't the resources, wasn't the people to get it and we were able to catch them while they were small and do it safely.'
Report Date	−1.352***	−0.589***	'I think the state of fuels is a big one, and I also think the **time of year** and the timing of the fire.' 'Regardless of the type complexity, whether it's a 1, 2, or 3, or 4 or 5, on a forest or jurisdiction, **that high PL levels are in the latter part of the summer months, generally – generally – will reduce your chance of getting the types of resources that you need**'
IMT Rank	−0.651***	−0.245***	' … **type 1 and type 2 teams - a lot of those teams are suppression- minded**' '**The best team is almost always – if not always - the local team**, it's the team that you know. It's your team. A lot of places have type 3 teams made up of local staff that live and work there all the time, they know the environment, they know the ground … when you start bringing in people from the outside, it starts getting more difficult.'
Unit Type (Jurisdiction)	−0.243*	−0.506***	'When you look at **state jurisdictional lands, and certainly private … In those cases, it's going to be full suppression, direct attack**, with indirect strategies' 'If there's **state jurisdiction involved, it's going to be minimize acres burned, aggressive, direct attack** to put the fire out.' 'There are a lot **more varied opportunities in the federal jurisdiction** than there is certainly on the private and the state'
Socioeconomic Variables			
Housing Unit Density	0.798*	0.542**	'You drive down a road you just thought was a logging road, and there's 20 houses at the end of it. That becomes a challenge for us because that **fundamentally changes how we approach the fire**.'
Seasonal Housing Unit Density	0.029	0.042	'Usually, you're into where we're burning houses down and you're in that kind of social/political realm when it bumps up to that type 1 team.'
Distance to Road/Rail	0.117	−0.046	'We look at tactics that we can actually do and be successful with, and that really points us toward more indirect strategies, and aerial ignition, and we can **back fire down to a road or something that is in place, you know a natural barrier**, because we just don't have the crews to go direct.'
Median Home Values	0.043	−0.133**	'If you're burning up in a high-end residential area, you're probably going to get more pressure not directly because of the cost, but just because **those people are more willing and knowledgeable in how to apply political pressure**.'
Temperature and Relative Humidity	N/A	N/A	'Generally to me it's when you either have favorable conditions that have occurred or are existing that allow you to shift your suppression strategy differently, or you have an unexpected event that takes place that is driven by fuel conditions or fire **weather conditions that change then allow you or force you to have to shift your strategy**'
Environmental and Fire Behavior Variables			
Cause of Ignition	0.397***	0.049	'Cause of ignition is a big one because **federal fire policy allows a lot more decision space in a natural fire start**.'
Terrain	N/A	N/A	'As far as terrain, **terrain is a huge influence on suppression methods**, especially nowadays with the beetle kill and the different state of our forests. Being able to find those places that are going to be good for holding the fire.'
Aspect	0.037	0.043	- (no quote mentioned aspect connected to suppression method)
Elevation	N/A	N/A	'If we can't fight the fire up there, we're not going to chase the fire up there. We're going to back off and fight the fire where we can.'
Primary fuel model	0.043	0.089**	'**Fuels and terrain, they certainly go without saying that's obviously going to influence your capabilities of suppression methods**'
Vegetation density	0.279***	0.171***	'Our forests are kind of overdue for fires, which makes them super dangerous for the folks on the ground. So we really got to look at the **fuel loading, the snag factor, and look at those suppression difficulty indexes** to see if we can suppress the fire where it's actually at.'
Area (log of)	0.794***	0.246***	'**If the fire gets to a certain size, you know you're not going to be able to do 100% suppression** on it.'
Perceived growth potential	−0.608***	−0.171***	'If you have a **fire that's moving from a federal jurisdiction where the fire may have initially been kind of a confine/contain or maintain/monitor**, and it moves out of that realm to an area in which you have **higher values at risk and potential for moving across to other jurisdiction, you need then to look at shifting your strategy to a more indirect/direct suppression strategy**'
Incident Duration	−1.366***	−0.669***	' … some of the more **regional/state/local teams, they're not going to commit those resources to longer duration fire**' 'If you have a specific mission to protect that specific value at risk and you need a specific resource to do it with, you identify that on the 209 that you need it for a **set duration**, it's more likely that you might receive that resource on a short duration and turnaround because they are on high demand'

Significance codes: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

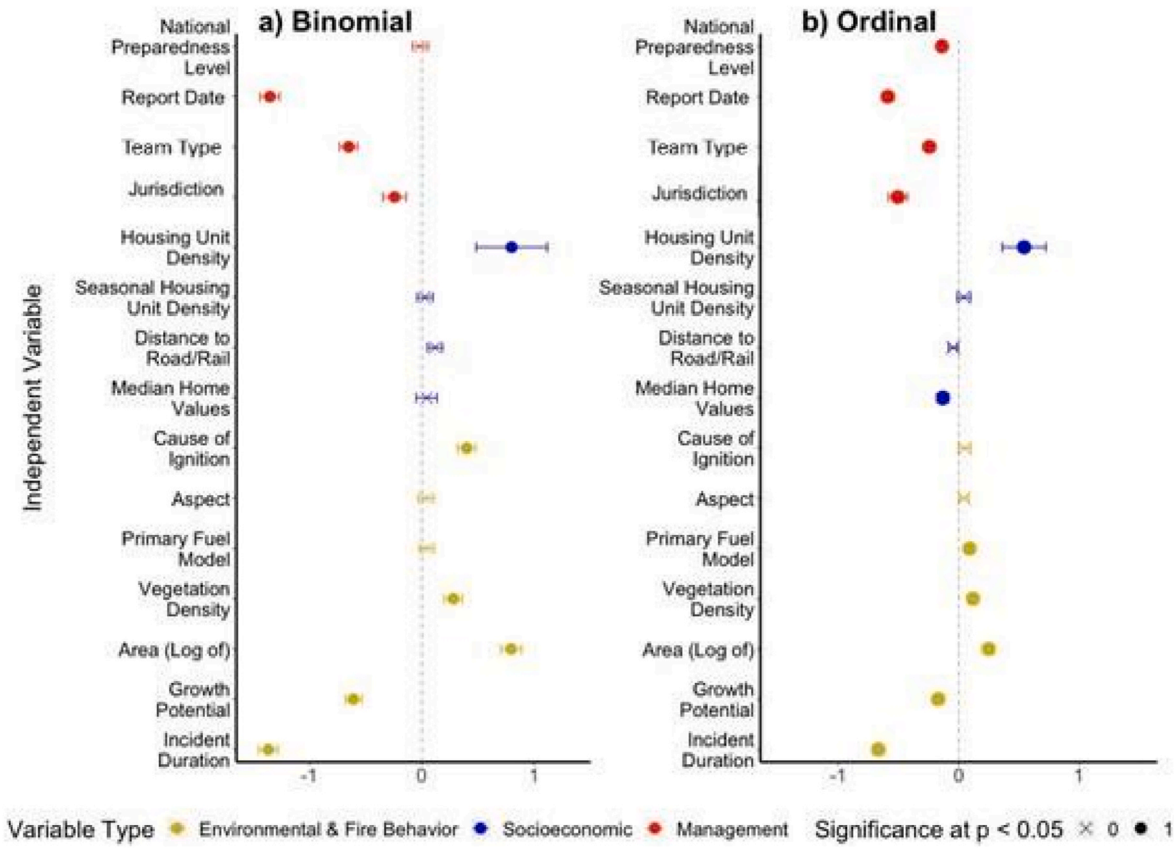

Fig. 2. Coefficients and standard error for the binomial regression model (adjusted $R^2 = 0.701$, n = 4751) and ordinal regression model (null deviance explained = 0.357, n = 4751).

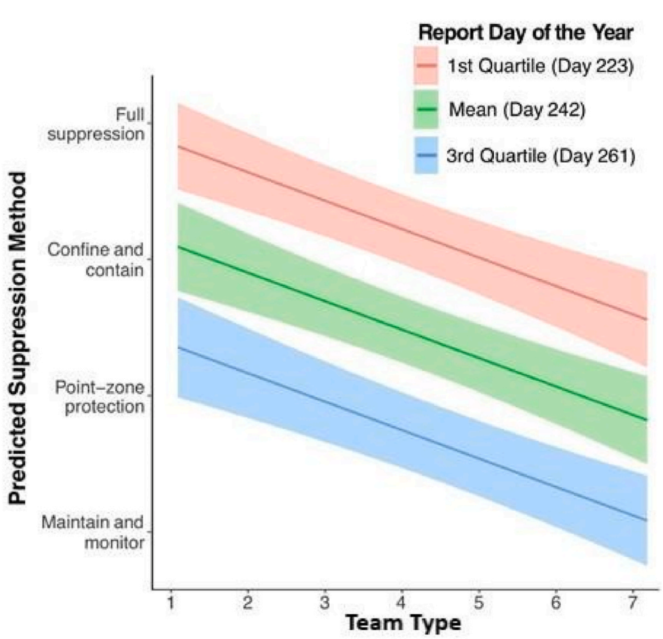

Fig. 3. Plot of the effects of team type on suppression method, cross-sectioned by report date from the ordinal regression (shading is 95% CI).

fires on federal lands managed adaptively as opposed to implementing full suppression (US Department of Interior and US Department of Agriculture, 2014), although interviewees noted that pressure for full suppression strategies remains high. Regional and national teams were more likely to suppress fire than local teams accustomed to the US northern Rocky Mountains landscape. Regional or national teams appear to choose full suppression and are also called in for fires with environmental conditions more likely to warrant full suppression.

Current and expected future resource availability were important drivers of commander decision-making. Commanders were more likely to select full suppression earlier in the year. As NPL increased later in the year, decision space decreased and there were insufficient resources to apply full suppression. This suggests that less-than-full suppression is often selected because the conditions and resources do not allow for full suppression. The conditions limiting decision space later in the year include drier fuels, reduced snowpack and water availability, depleted fire funding, and resource scarcity (Belval et al., 2020). Commanders could take advantage of less extreme conditions earlier in the year by selecting less-than-full suppression, enhancing effectiveness with more resources available later in the year (Thompson et al., 2018).

4.2. Future conditions require increased decision space

The combination of WUI housing growth and hot, dry conditions magnified by climate change creates dangerous fire conditions around the world, and rates of WUI development and climate change are expected to continue (Brown et al., 2004; Littell et al., 2009; Westerling, 2016). More extreme fire conditions in fire-prone forests with an increasing number of structures will likely reduce the decision space for selecting less-than-full suppression methods (Chas-Amil et al., 2013). Additionally, safety measures to reduce risk during pandemics, such as those implemented due to the COVID-19 outbreak, will further restrict decision space (Moore et al., 2020). Reducing housing and utility development in the WUI or incorporating community risk reduction plans is critical. Given an increase in large fires and extreme fire conditions since the early 2000s and projected into the future, it may be

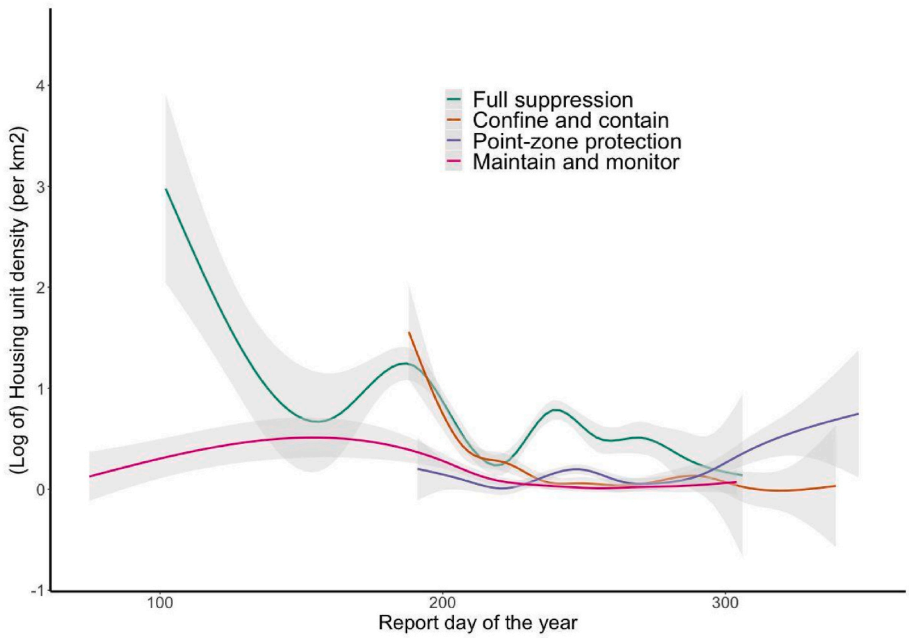

Fig. 4. Suppression methods by report day of the year and housing unit densities (standard error is shaded). See Table S3 for suppression method reporting date ranges.

difficult for commanders to identify low-risk opportunities for less-than-full suppression. However, it will be increasingly important to allow certain fires to burn under moderate conditions, which could help reduce fire in some forest types during hot, dry conditions. Increased decision space requires policy shifts toward adaptive fire management at the local and federal levels (Schoennagel et al., 2017; Hessburg et al., 2021; Platt et al., 2022). Reducing uncertainty in decision making with respect to both wildfire effects and social values can improve decision makers' risk assessments, including for less-than-full suppression decisions (Thompson and Calkin, 2011).

Shifts in agency culture and communications are needed to increase the decision space for less-than-full suppression (Calkin et al., 2011; Steelman and Burke, 2007). Interviewees mentioned the agency rhetoric used in policy language or public communications impacts public perception and the default response to wildland fire (Thompson et al., 2018). Commanders suggested agency leadership acknowledge the value of fire on the landscape and communicate about fire as natural, such as redefining the language of 'suppression' to 'managing a fire' and shifting identity from firefighter to fire manager or fire professional. Indeed, incentives may allow agency personnel or communities to see value in fire on the landscape (Higuera et al., 2019). Additionally, including key performance indicators that balance safety, costs, and beneficial effects of fire could help realign commander incentives and improve incident response system functionality by streamlining agency messaging (Thompson et al., 2018). Societal expectations for liability are changing with increased line officer liability for fire losses, causing commanders to become more risk averse (Canton-Thompson et al., 2008), which can impede their choice to allow fires to burn. Expanding wildland fire use teams could encourage additional use of less-than-full-suppression in the future, offering some expansion of the decision space (McCaffrey et al., 2013). Evidence suggests that the 2009 Guidance for Implementation of Federal Wildland Fire Management Policy, which provided more flexibility for less-than-full suppression approaches, has been effective in shifting some fire responses away from full suppression, based on an analysis of 209s (Young et al., 2020). If federal and state policies expand autonomy and create recognition platforms to select less-than-full suppression methods, we may see an increase in the selection of those methods (Steelman and McCaffrey, 2011). Wildfire decision support tools are increasingly available, potentially enabling better support for choosing less-than-full-suppression (Calkin et al., 2011). However, managers often report using these tools to justify decisions they have already made, undermining their effectiveness (Noble and Paveglio, 2020; Schultz et al., 2021).

Equity in wildfire response is an important consideration. Our study did not find a consistent effect of median home value on wildfire suppression type. The binomial model was consistent with the assumption of Gude et al. (2013) that wildfire responders would not differentiate between expensive and inexpensive homes. The ordinal model showed full suppression was actually somewhat more likely in areas with less expensive homes. Some prior research has shown wildfire agencies are more responsive in creating wildfire risk reduction projects in wealthier areas with more residents who are white (Anderson et al., 2020). Furthermore, historical indigenous burning practices have shaped today's fire-adapted landscapes and a resurgence of interest calls for better incorporation of traditional ecological knowledge in future fire management, which could influence wildfire response (Lake et al., 2017; Souther et al., 2023).

4.3. Combining quantitative and qualitative data strengthens inferences

Combining quantitative and qualitative data can strengthen research validity and inferences by triangulating results and buttressing the weak points of both approaches (Creswell and Clark, 2017; Johnson and Turner, 2003). For instance, quantitative data have limits such as multicollinearity and spatial and temporal autocorrelation, while qualitative interviews can inform the interpretation of data under these conditions. Qualitative data may not be statistically representative but can be interpreted alongside a regression that identifies multivariate relationships. We encourage intertwining these methods to enhance validity and provide greater context that can make quantitative results meaningful to multiple audiences.

Future research could expand this work over a larger region and time period, to include additional geographic and social contexts of wildfire response and as national fire policy continues to evolve. Weather is a well-established driver of fire activity and commander decision-making; thus, future studies should disentangle the relative importance of weather and the variables in this study. State was highly correlated with latitude/longitude and had to be removed from the models even though commander interviews, previous studies, and descriptive statistics suggested Idaho was more likely than Montana to manage with less-than-full-suppression. Future studies may investigate the role state policy has in suppression method selection. US fire suppression policies have predominantly focused on forested areas (Reiners, 2012), but in recent decades the majority of area burned in the conterminous US was on non-forested lands. Fires on non-forested areas tend to be larger, and rapid expansion of invasive grasses are driving changing fire regimes (Crist, 2023). Fire managers face complex ecosystem and socioeconomic contexts and risks in making fire suppression choices (Steelman, 2016).

5. Conclusions

These results indicate management and socioeconomic factors such as jurisdiction, report date and NPL, home values, and team type are important to add to the topographic and fire characteristics that are more commonly used to explain fire management decisions. Support for wildfire coexistence and less-than-full suppression when appropriate will require changes in management, such as more fire-adaptive rhetoric by agencies, to support commander decisions that include the complex social-ecological context for fire. Proactive federal, state, and local policies incentivizing less-than-full-suppression will be increasingly important as global WUI development and climate change constrain the decision space in which fire commanders operate.

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Credit authorship contribution statement

Molly C. Daniels: Conceptualization, Methodology, Writing – review & editing, Data curation, Formal analysis, Investigation, Project administration, Software, Visualization, Writing – original draft. **Kristin H. Braziunas:** Conceptualization, Methodology, Writing – review & editing. **Monica G. Turner:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Ting-Fung Ma:** Methodology, Software, Writing – review & editing. **Karen C. Short:** Data curation, Methodology, Resources, Writing – review & editing. **Adena R. Rissman:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119731.

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