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Review

Patterns of wildfire risk in the United States from systematic operational risk assessments: how risk is characterised by land managers

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Abstract. Risk management is a significant part of federal wildland fire management in the USA because policy encourages the use of fire to maintain and restore ecosystems while protecting life and property. In this study, patterns of wildfire risk were explored from operational relative risk assessments (RRA) completed by land managers on 5087 wildfires from 2010 to 2017 in every geographic area of the USA. The RRA is the formal risk assessment used by land managers to develop strategies on emerging wildfires when concerns and issues related to wildfire management are in real-time. Only 38% of these wildfires were rated as high risk and 28% had high ratings for values at risk. Large regional variations were evident, with the West Coast regions selecting high risk and the South-west and Eastern regions selecting low risk. There were finer-scale influences on perceived risk when summarised on a jurisdictional level. Finally, risk summarised by USA agencies showed that the National Park Service and USDA Forest Service selected high risk less frequently compared with other agencies. By illuminating patterns of risk, this research intends to stimulate examination of the social, cultural, and physiographic factors influencing conceptions of risk.

Keywords: geographic area, federal, fire management, relative risk assessment, Wildland Fire Decision Support System.

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Introduction

Wildland fire, climate variability, people and vegetation have interacted over long time periods to produce vast fire-dependent ecosystems in the USA (Stewart 1951; Vale 2002; Whitlock *et al.* 2010; Marlon *et al.* 2012). Early in the 20th century, policy makers focused on the extraction of forest resources to fuel westward migration and implemented a fire policy that directed all fire ignitions to be extinguished by 10 a.m. the next morning (Loveridge 1944). By the 1960s, momentum was building to restore fire to some affected ecosystems, primarily in the National Park Service (NPS) lands followed later in USDA Forest Service (USFS) wilderness areas (van Wagtendonk 2007; Smith 2014). Iterations of the USA fire policy have since evolved to recognise fire as a 'critical, natural process', with the use of wildland fire as an important component of land management (Zimmerman and Bunnell 2000). In practice, using and suppressing fire together is complex and it has become more important to place fire management decision-making within a risk framework to ensure success and accountability.

Risk is the expectation of loss or benefit based on the probability and consequence of uncertain future events (Finney 2005; Ager *et al.* 2010; Calkin *et al.* 2010; Yoe 2011; Miller and Ager 2013; Scott *et al.* 2013; Thompson *et al.* 2016*a*). Although its definition is clear, risk is more difficult to articulate consistently when establishing strategies, goals and objectives for emerging wildfires, which can require quick decisions in chaotic environments. Consequently, it is not unusual for differences in the perception of risk and disparate risk management practices to exist among land managers, even for the same incidents (Thompson *et al.* 2016*b*).

Risk perceptions inherent in operational risk assessments are influenced by a multitude of factors, including assumptions, recent memories, quality, skill and bias associated with professional judgements, perceived affect and real risk (Tversky and Kahneman 1973; Alhakami and Slovic 1994; Sjöberg 2000; Kahneman and Klein 2009; Johnson-Laird 2010). These factors can lead to risk aversion in fire management decision-making, attributed to mental shortcuts developed during uncertain and conflicting decision environments (Maguire and Albright 2005). In one study, costly and risk-intolerant management strategies were favoured by fire managers given social and political constraints simulated in hypothetical scenarios (Calkin *et al.* 2013). Other studies have shown that risk-accepting behaviour is also present during wildfires. For instance, managers with extensive experience were more likely to identify long-term considerations as important and tended to support the use of wildfires in wilderness areas when selecting fire management

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strategies from hypothetical scenarios (Wilson *et al.* 2011), suggesting that some combination of experience, perspective and individual risk tolerance plays an important role in deciding whether to use wildland fire for ecological benefit. Similarly, a commitment to return fire to fire-adapted landscapes was the most significant factor influencing fire managers to use wildfire in a study by Williamson (2007).

Overcoming the potential constraints imposed by risk perception has manifested as solutions such as those proposed by Marcot *et al.* (2012), with formal procedures encompassing the four stages of structured decision-making, which can be used in an operational wildfire context (Taber *et al.* 2013) to facilitate strategic decisions that promote the use of fire. Ultimately, when the risk of fires interacting negatively with values at risk is recognised and mitigated consistently, it becomes possible to implement more strategies that allow fire to do its work, as sought in federal fire policy (Young *et al.* 2020).

In part to promote consistency in risk assessment in the USA, the Wildland Fire Decision Support System (WFDSS) incorporates a systematic operational risk assessment tool called the relative risk assessment (RRA) for emerging fires on federal lands (NIFC 2021). The RRA belongs to a collection of data, models and tools for evaluating expected fire behaviour, cost, damage and ecological benefit, among other things, in the context of guidance from legally binding land management plans (Calkin *et al.* 2011; Noonan-Wright *et al.* 2011; Pence and Zimmerman 2011; Zimmerman 2011; Zimmerman 2012). Development of the WFDSS and its RRA capitalised on the emergence of national-scale cadastral and critical infrastructure data in the USA, which together with spatial fire models, allowed managers to better quantify threats and hazards to values at risk. The WFDSS includes a formal decision process mandated for federal wildland fires that have exceeded the period of time considered to be the initial response (NIFC 2021). Some managers have used the WFDSS primarily to document decisions already made and others have found it useful for facilitating strategic, collaborative decision-making (Noble and Paveglio 2020; Rapp *et al.* 2020). Regardless of its perceived utility, the WFDSS has been an important step in advancing risk assessment of wildland fires in the USA (Finney 2005).

The RRA is a semiquantitative process enabling fire managers to assign relative rankings to risk elements using predetermined categories and terminology (Philpot *et al.* 1995; Thompson *et al.* 2016*b*). Each RRA includes high, moderate and low ratings for three elements (Values, Hazard and Probability) which are collectively integrated into an overall Relative Risk rating. The RRA elements are derived subjectively through deliberation by small groups of local decision-makers informed by observation, models and data. RRAs are real-time assessments of risk that guide planning and management of incidents and are one of three components used to evaluate incident complexity, in addition to identifying fire fighter safety issues and the appropriate incident management organisation (NWCG 2014). As such, they provide snapshots of how land managers, administrators and fire specialists with access to state-of-art data, models and analysis tools assess the risk of thousands of wildfires while they are burning. Over the life of an incident, many RRAs may be produced to reflect the risk of a dynamic fire environment. These assessments inform the fire management strategies outlined in the WFDSS decision signed by an agency administrator and because they document largely initial, subjective risk specific to an individual fire, they are termed 'relative' risk assessments (T. Zimmerman pers. comm.).

In this study, RRAs from completed assessments in the USA from 2010 to 2017 were examined to gain insights into the risk profiles shaping fire management decisions. The purpose of this research was to identify patterns in wildfire risk perceptions; specifically, risk evaluated at the national, regional and unit scales, as well as among the different land management agencies. The research focused exclusively on the RRA in the WFDSS and sought to answer the following questions:

1. What is the wildfire risk profile for long-duration, federal fires in the USA?
2. Does risk and the factors leading to it vary by geographic area (GA)?
3. Are differences in risk evident at scales finer than GA?
4. Do the federal land management agencies differ in selection of risk?

Methods

Data sources

The data used in this analysis was obtained from the WFDSS. In addition, the Fire Occurrence Database (FOD) was used to contextualise fires reported in the WFDSS relative to total fire load (Short 2017). Information regarding the incident management teams was summarised from the National Interagency Fire Center (NIFC) (NIFC 2017). The RRA consists of categorical data, with users selecting high, moderate, and low ratings for nine sub-elements to produce ratings for the main elements of Values (at risk), Hazard, Probability, and ultimately Relative Risk (Fig. 1, Table 1). Users also write qualitative justifications for each specific element. The ratings of each sub-element are integrated in graphical tables to assign ratings to each risk element (Values, Hazard, Probability). The final Relative Risk rating is then derived from the three main elements in a similar graphical table (Fig. 1).

The RRA is used for wildfires occurring in federal jurisdictions and by some states (New Mexico, Arizona and Alaska) and is targeted for emerging incidents that are expected to cause containment problems or burn for a long duration. For context, there were 616 032 wildfires in the USA from 2010 to 2017 (Short 2017). Of these, ~17% were fires on federal lands. Among federal fires, 4.9% resulted in publication of a risk assessment in the WFDSS. This analysis, then, provides insights into risk on mostly federal lands for wildfires that were expected to pose management challenges.

Data collection

The WFDSS is a J2EE, java server faces web application that integrates technologies to store, create, query and display geospatial and tabular data through the application server and other services (Calkin *et al.* 2011; Noonan-Wright *et al.* 2011). Data stored in the relational data stream management system were queried though the use of structured query language to link data tables and to extract information.

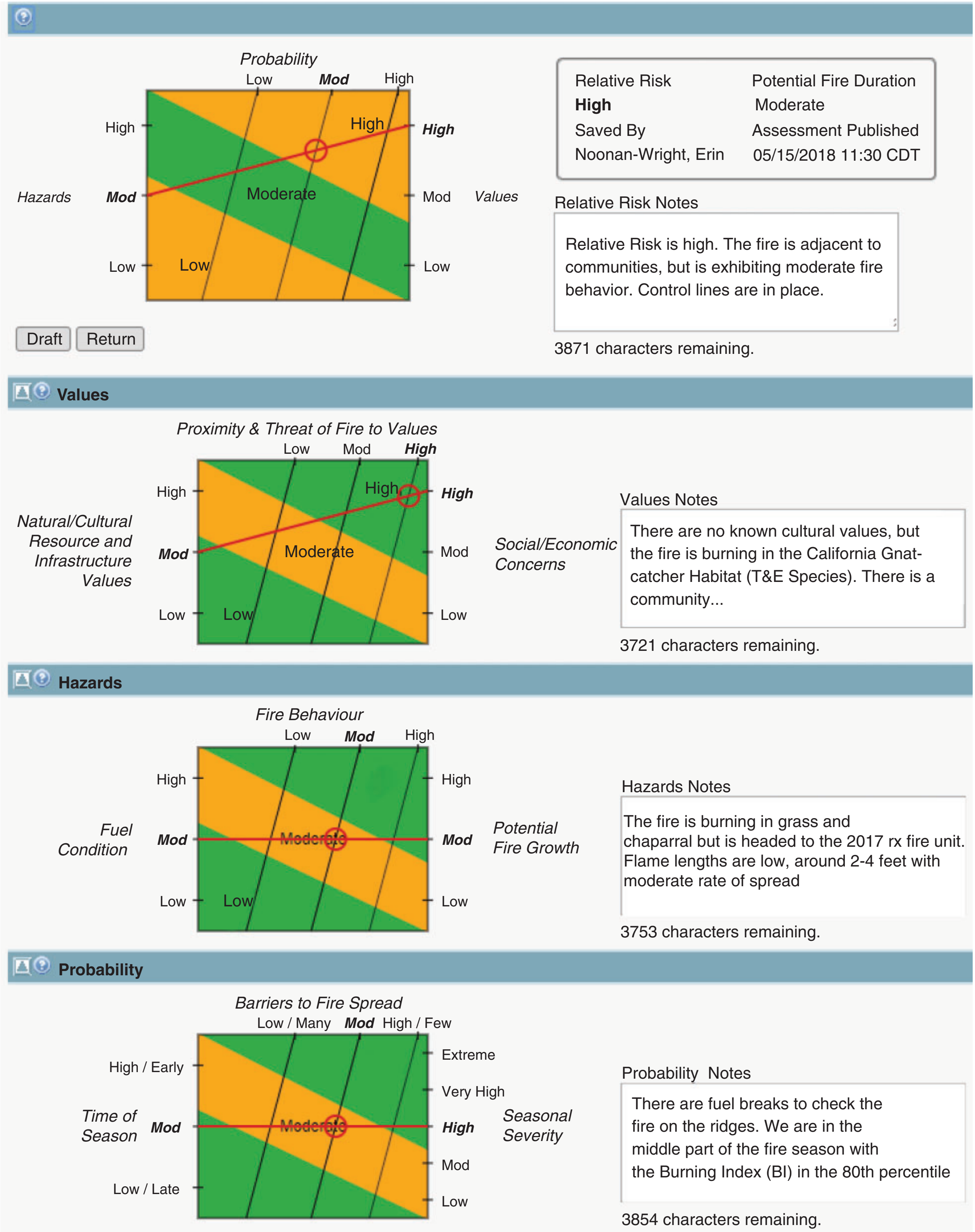

Fig. 1. Relative risk assessment in the Wildland Fire Decision Support System (WFDSS). There were subjective combinations of sub-elements that were derived from the 1998 Wildland Fire Use Policy guide (USDI/USDA 1998). These were further revised in response to the Cerro Grande Prescribed Fire Review Investigation Report Recommendations (NIFC 2000).

Table 1. Description of the elements (Values, Hazard and Probability) and their sub-elements that are rated as high, moderate or low to produce a Relative Risk rating

Element	Sub-element	Description
Values		Ecological, social and economic resources that could be improved, lost or damaged because of a fire
	Natural, cultural resources and infrastructure values	Ecosystem resilience to disturbance; presence of artefacts or cultural sites and how they respond to wildfire; property and infrastructure
	Social and economic concerns	Impacts to businesses, communities, tribal subsistence, air quality; impacts on the public including closures
	Proximity and threat of fire to values	The threat to values at risk, given their proximity to the fire
Hazard		The conditions, fire spread and intensity and spatial extent of the fire
	Fire behaviour	The current and expected fire behaviour (surface, crown, spotting)
	Fuel condition	Fuel loading and continuity, fire return interval
	Potential fire growth	Expected fire growth given weather and control efforts
Probability		The likelihood of a fire becoming an active event
	Time of season	The potential for a long-duration event and relationship to the historical fire season
	Seasonal severity	Fire danger indices, drought and live fuel moistures
	Barriers to fire spread	The natural defensibility of the fire's location, including natural and unnatural barriers (ridges, roads etc.)
Relative Risk		The relative risk assessment (RRA) that results from independent assessments of Values (at risk), Hazard and Probability. The RRA is intended to characterise the general magnitude of risks associated with the fire itself at a specific point in time

Duplicates and other anomalies with the data were remedied using CRAN – R (R Core Team 2019) and various packages to compute time (Grolemund and Wickham 2011), create and append data tables (Wickham 2007, 2014, 2016) and expedite processes (Bache and Wickham 2016). A total of 36 variables were extracted from the WFDSS, including numeric (mostly discrete) and categorical (a mixture of ordinal and nominal) data types. Qualitative notes were included in the RRA dataset as '_notes' variables (Supplementary Table S1, available online), but not used explicitly for this analysis.

Because numerous RRAs can be completed during an incident, the first instance of the most frequently occurring Relative Risk rating was selected to represent the Relative Risk for that incident. In the case of incidents having only one high, moderate or low RRA, the first rating was chosen to represent that incident's Relative Risk. This resulted in 5087 unique RRAs representing individual wildfires from 1 January 2010 to 31 December 2017. RRAs are published at inconsistent time intervals for a variety of reasons, such as a need to annotate the existing semiquantitative ratings, to polish a RRA for inclusion into the authoritative WFDSS decision or to reflect real changes in risk such as an increase in fire behaviour. Although the method of selection used in this research excluded some of the incident RRA data, it allowed for each incident to contribute equally, without giving preference to those fires with many published RRAs. For context, there were 12 324 risk assessments on the 5087 fires used in this analysis. There were 4.6% more high ratings, 3.6% fewer low ratings and a negligible difference in moderate ratings (<1%) among all risk assessments compared with the incident-specific selection used in this study.

Scales of analysis

Risk was first summarised nationally, then regionally (referred to as GA) and finally at the unit scale (e.g. individual national forests, field offices, refuges, reservations and national parks in the western USA). GA is a codified institutional level of organisation in which wildfires are prioritised and resources allocated (Fig. 2). An additional analysis was also completed at the agency-level to examine differences among the five major federal agencies responsible for managing land in the USA, including the Bureau of Land Management (BLM), USDA Forest Service (USFS), U.S. Fish and Wildlife Service (USFWS), the Bureau of Indian Affairs (BIA) and the National Park Service (NPS).

Frequency analysis

Computing observed frequencies

The observed frequencies of high, moderate and low risk (expressed as percentages) were computed from counts of individual ratings for Relative Risk, the risk elements and the sub-elements. Counts were produced for 10 GAs and for the USA as a whole. Each tally was divided by the total for each respective GA to produce frequencies (expressed as percentages).

Computing expected frequencies from chance

The expected frequencies of high, moderate and low risk (expressed as percentages) were computed from all possible combinations of sub-element ratings ($n = 32\,805$) for Hazard, Values, Probability and Relative Risk based on a random selection of risk ratings for each sub-element. Expected frequencies for sub-elements were one in three (33.3%) except for seasonal severity, which was one in five (20%). These frequencies are referred to as '% expected' in the proceeding analyses and graphs.

Relative frequencies

Observed frequencies (% observed) were normalised to USA frequencies in order to express risk relative to the national picture (% $\text{observed}_{\text{U.S.}}$). The selection metrics were computed

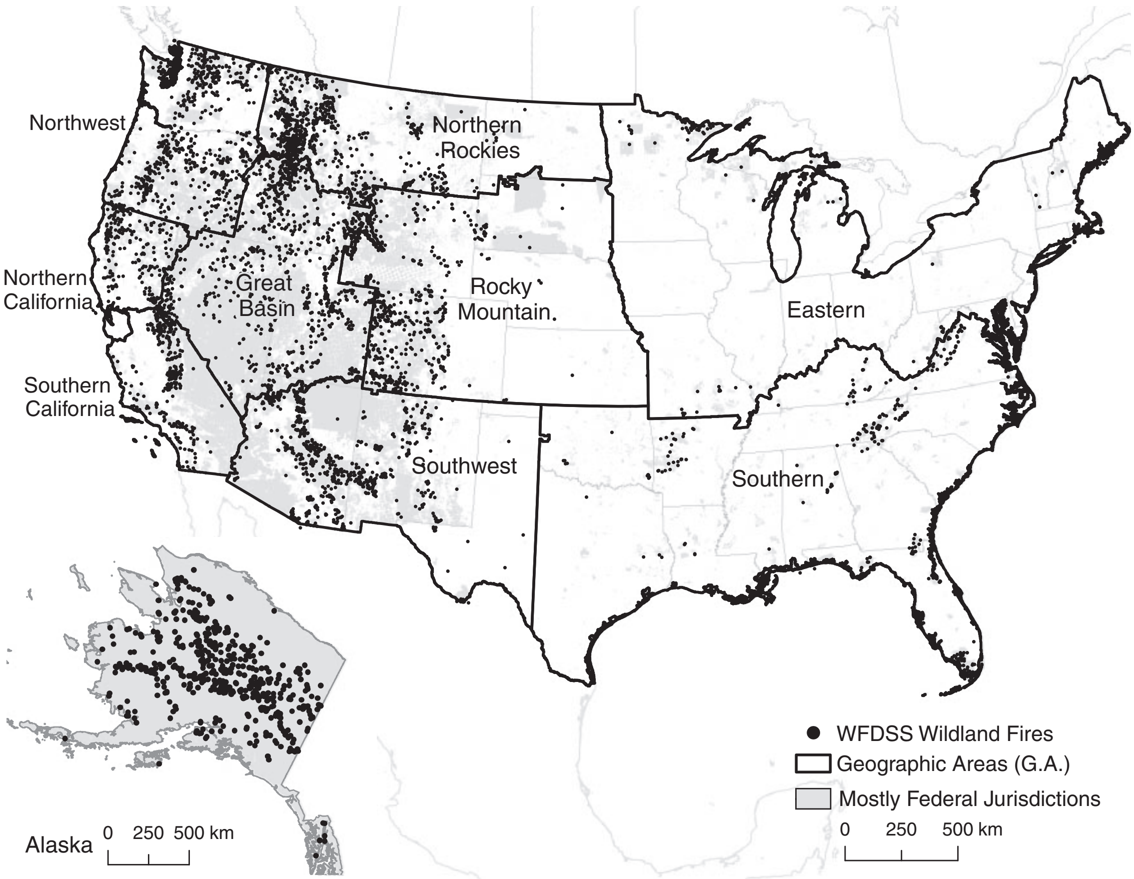

Fig. 2. Locations of the 5087 wildfire incidents (with published relative risk assessments) within the 10 geographic areas and in relation to mostly federal lands.

to show the propensity to select specific ratings compared with the USA value:

$$selection\ metric_{U.S._i} = \frac{\%\ observed_{j,k}}{\%\ observed_{U.S._{j,k}}} - 1$$

where: $selection\ metric_{U.S._i}$ = unit-less index showing the selection of ratings for each of the (i) GA compared with the percent observed frequencies for the collective USA; $\%\ observed_{j,k.}$ = percent observed frequencies for each (j) rating (high, moderate or low) by (k) Relative Risk, element, or sub-element; $\%\ observed_{U.S_{j,k}.}$ = percent observed frequencies of the USA for each (j) rating (high, moderate or low) by (k) Relative Risk, element or sub-element.

In sum, the selection metric revealed a propensity for GAs to select specific ratings more or less relative to the USA. In the interest of simplifying the interpretation, 1 is subtracted from the relative frequency such that resulting negative values become the actual percentage difference between observed and expected; for example, –0.20 means that particular rating was chosen 20% less than the national percentage. For positive values, 1 is added back to the value and the interpretation is that a region used a particular risk level more than what was expected for the USA; for instance, a value of 2.5 indicates a 350% higher usage than expected.

Analysis techniques

Cluster analysis

Agglomerative hierarchical cluster analysis was performed on observed frequencies of risk for each GA and the USA to explore how GAs share or isolate selection of risk and its elements, with no scaling because the data were already scaled to percentages. Distance was measured as squared Euclidean distance using Ward's method for a similarity metric, which evaluates an increase in the sum of squares as group membership changes. The 'hclust' function in CRAN – R was used to produce the dissimilarity matrices and clustering.

The observed frequencies of all 27 possible combinations of Values, Hazard and Probability were used as inputs. In addition, the frequencies of each sub-element combination were used to assess how GAs grouped based on the individual elements of Values, Hazard and Probability. For example, to cluster GAs for the Values element, observed frequencies for all combinations of high, moderate and low resources, threat and concern were used.

Location quotient

A spatial metric called the location quotient (Unwin 1981) was used to highlight concentrations of high Relative Risk by jurisdictional unit in the western USA to examine fine-scale patterns of Relative Risk. Unit refers to geographic management areas within agencies; for example, individual national forests, national parks, reservations and wildlife refuges. The location quotient shows geographic concentrations (e.g. Shaw and Wheeler 1985) and measures the extent to which different GAs depart from some norm (LQ > 1.0 depicts concentrations and vice versa). For this analysis, it depicted concentrations of high Relative Risk relative to the national occurrence of high Relative Risk. Each unit needed at least three incidents to be included in the analysis: 24 incidents on average were used to calculate the LQ at the unit level. LQ was defined as:

$$LQ = \left(\frac{X_i}{X}\right) / \left(\frac{Y_i}{Y}\right)$$

where X_i = frequency of high Relative Risk ratings, *i*, in any given jurisdiction or unit; X = sum of all high Relative Risk ratings in a GA; Y_i = frequency of high Relative Risk ratings, *i*, at the national level; Y = sum of all the high Relative Risk ratings for the USA.

Results

What is the wildfire risk profile for long-duration, federal fires in the USA?

Nationally, a slight majority of fires (n = 1915, 38%) received a moderate Relative Risk rating, followed by high (n = 1913, 37.6%) and low (n = 1239, 24.4%). Land managers favoured moderate (52.1%) and high (30.2%) for the Probability element. They selected low (37.3%) and moderate (35.9%) for Values at risk. Hazard was the most symmetrical element, with a preference for moderate (41.6%) and roughly equal proportions of high and low (Fig. 3).

Approximately 40% of fires were expected to have little effect on natural, cultural resources and infrastructure (resources) or few socioeconomic (concerns), while 25% were close to Values at risk (threat) and expected to reach them without mitigation (Fig. 4). Observed and expected fire behaviour was low to moderate for 84% of fires and most (78%) were expected to experience little to moderate fire growth and provide low to moderate resistance to fire control (potential). Barriers to fire spread were absent for 19% of fires, numerous for 31%, with ~80% having at least some barriers limiting fire spread. Individually, the sub-element frequencies illustrated moderate to low ratings roughly 80% of the time (on a per-sub-element basis).

Does risk and the factors leading to it vary by GA?

General patterns emerged when risk was summarised by GA. The South-west and Eastern GAs selected low Relative Risk; the North-west, Northern California and to a lesser extent Southern California used high Relative Risk and the other regions fell in between (Fig. 5). These patterns were pronounced relative to the risk frequencies of the USA as a whole (Fig. 6). The Great Basin risk profile was essentially identical to the National (average) profile, followed closely by the Southern, Northern Rockies, and Rocky Mountain GAs. All of the regions used low Relative Risk more than expected (Table 2). The North-west and Northern California stood out as the only regions using high Relative Risk more than expected (Table 2, Fig. 5).

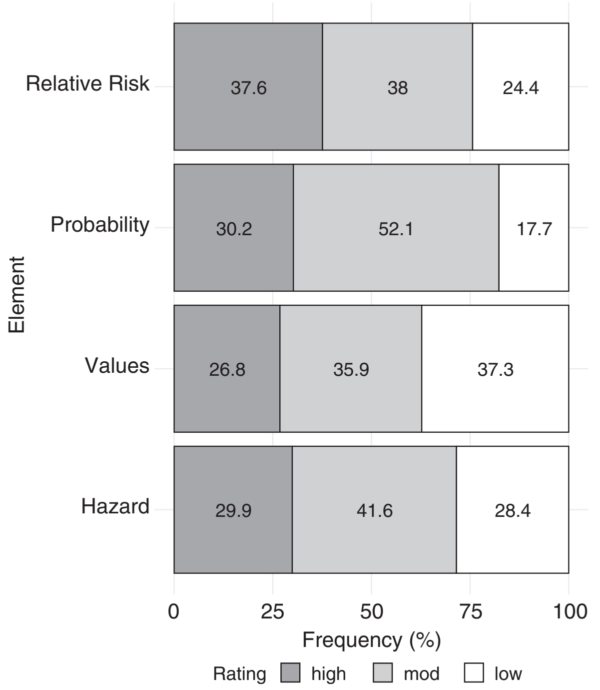

Fig. 3. Relative frequencies for the risk assessment and its elements in the USA.

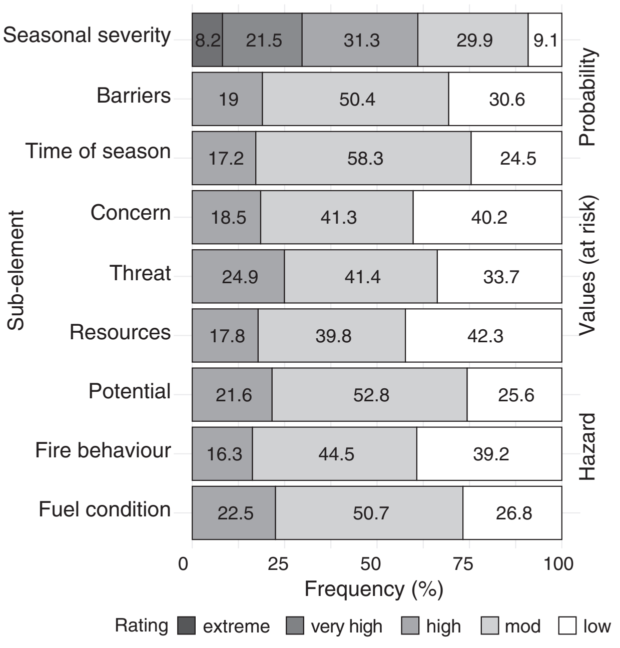

Fig. 4. Frequency of sub-element usage for the US. Seasonal Severity has five options for ratings while the other sub-elements have three (low, moderate, high).

A dendrogram created by hierarchical clustering of the main risk elements produced four general risk groups consistent with the patterns described above (Fig. 7). GAs on the West Coast made up a high-risk group; South-west and Eastern formed a

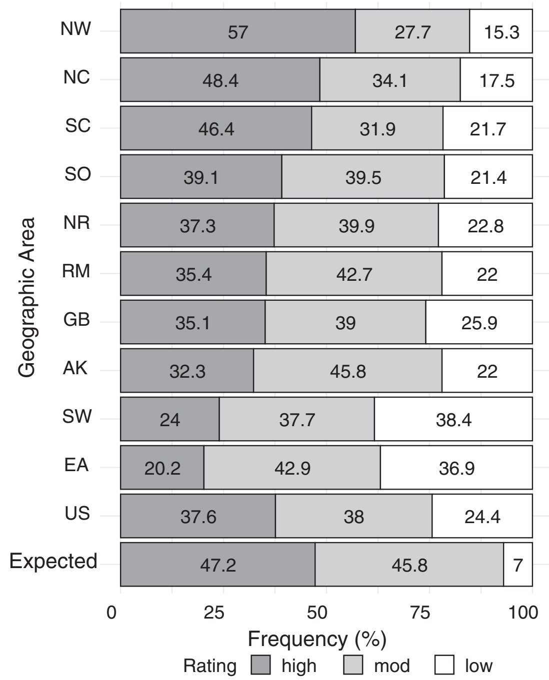

Fig. 5. Relative Risk by geographic area. North-west (NW), Northern California (NC), Southern California (SC), Southern (SO), Northern Rockies (NR), Rocky Mountain (RM), Great Basin (GB), Alaska (AK), South-west (SW), Eastern (EA), United States (US) and expected frequencies.

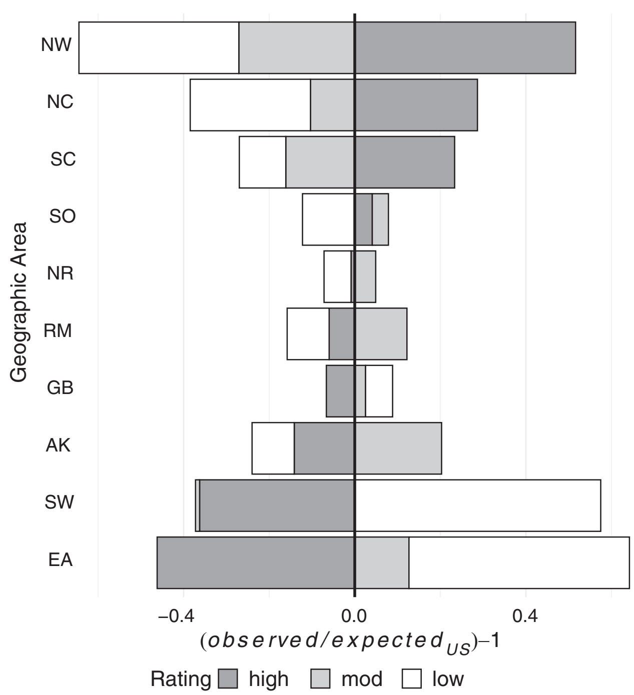

Fig. 6. Geographic area Relative Risk ratings compared with the US (average) ranked from highest to lowest usage of high Relative Risk. Positive values show higher usage for specific ratings while negative values depict less frequent usage.

low-risk group; Rocky Mountain, Great Basin and Southern were a National Average group; and Alaska and Northern Rockies made up a National Average subgroup that tended to perceive somewhat lower Values at risk and higher Probabilities than the National Average group.

Clustering individually on risk elements revealed other differences. The Northern Rockies, Alaska and Eastern formed a low Value cluster. Northern California, the North-west and Southern California clustered separately as high Value. The rest of the GAs clustered in the middle (Fig. 7). Southern joined the high-risk group of Northern and Southern California and the North-west for Hazard. The remaining GAs clustered together in unique patterns: Rocky Mountain and Great Basin; USA and Alaska; Northern Rockies and South-west. Probability produced the familiar low-risk group of Eastern and South-west, a moderate probability group (Rocky Mountain, Great Basin, Southern, Alaska and the USA), and the Northern Rockies joined the high-risk group of the North-west, Northern and Southern California.

Generally, moderate to low ratings were selected by all GAs for all sub-elements (Fig. 8). Overall, natural-cultural-infrastructure (Values), socioeconomic concerns (Values), threat to (Values) and fire behaviour (Hazard) trended low compared with the other sub-elements. Some specific regional differences were also evident when the GAs were compared with the USA. For example, fuel condition (Hazard) posed an elevated risk in Northern California, Southern California, the North-west and Southern relative to the other GAs and fire was more proximate to (Values) in the two California regions and the North-west. Barriers limiting fire spread (Probability) were more prevalent in the South-west and Eastern and less so for about one-quarter of the fires in the North-west. Seasonal severity (Probability) was more often extreme and very high in Southern California, Northern California, Northern Rockies, North-west and arguably for the Eastern Region, which selected extreme seasonal severity more than any other GA. Almost half of South-west fires occurred late in the season (Probability), which is rarely the case for Alaska, and can occur throughout the fire season in the Southern and Eastern GAs. Potential for fire spread (Hazard) was comparatively low in Eastern, South-west and to a lesser extent Rocky Mountain and was high in North-west, Northern California, Alaska and the Northern Rockies. Socioeconomic concerns (Values) were lower in the South-west and Alaska and higher in Southern California and the North-west, while resource and infrastructure (Values) were lower in Alaska, Northern Rockies and Eastern and relatively high in Northern California and North-west. Southern California had fewer natural resource/infrastructure values and more socioeconomic concerns relative to Northern California.

Specific patterns belonging to individual GAs emerged from federal fire information contained in the WFDSS and provided context for the selection of risk ratings. Formal use of the risk assessment was highly variable among the GAs. Alaska and the Great Basin published risk assessments on 12.6% and 4.6% of wildfires, respectively, while half of the GAs produced risk assessments less than 1% of the time, suggesting that most wildfires were either not federal or easily extinguished. Wildfires with published risk assessments were generally longer in duration, with ~22 days between the start and containment.

Table 2. Relative risk by geographic area and the US

Observed frequencies by geographic area and the USA of elements from the Relative Risk assessment. Expected frequencies (Exp.) are included to allow comparisons with random chance

Element	Exp. (%)	US (%)	Great Basin (%)	Rocky Mtn (%)	Southern (%)	Alaska (%)	Northern Rockies (%)	Northern California (%)	North-west (%)	Southern California (%)	Eastern (%)	South-west (%)
High Relative Risk	47.2	37.6	35.1	35.4	39.1	32.3	37.3	48.4	57.0	46.4	20.2	24.0
Mod Relative Risk	45.8	38.0	39.0	42.7	39.5	45.8	39.9	34.1	27.7	31.9	42.9	37.7
Low Relative Risk	7.0	24.4	25.9	22.0	21.4	22.0	22.8	17.5	15.3	21.7	36.9	38.4
High Values	33.3	26.8	28.5	26.4	26.0	18.6	21.2	36.9	42.2	35.2	10.7	19.2
Mod Values	48.1	35.9	33.9	38.1	37.2	34.9	37.8	35.5	33.0	35.9	45.2	37.3
Low Values	18.5	37.3	37.7	35.6	36.8	46.5	41.0	27.6	24.8	28.9	44.0	43.6
High Hazard	33.3	29.9	27.0	27.2	33.6	26.2	29.2	42.4	46.4	35.5	14.3	18.9
Mod Hazard	48.1	41.6	43.6	46.9	45.4	46.9	40.8	34.1	33.3	37.5	38.1	42.7
Low Hazard	18.5	28.4	29.4	25.9	21.1	26.9	30.0	23.5	20.3	27.0	47.6	38.4
High Probability	35.6	30.2	23.5	25.1	29.9	29.2	36.8	39.6	44.5	34.5	23.8	19.6
Mod Probability	44.4	52.1	57.2	56.7	50.7	60.9	54.1	45.6	45.9	54.3	45.2	41.5
Low Probability	20.0	17.7	19.2	18.2	19.4	10.0	9.1	14.7	9.6	11.2	31.0	38.9

Alaska, the Northern Rockies and the North-west GAs had the longest duration fires, with the Eastern, Southern, Rocky Mountain and the Great Basin having the shortest (Table 3).

Utilisation of incident management teams (IMT) also varied by region. IMTs are generally used to manage longer duration fires that have a high probability of affecting values at risk, with a Type 1 IMT used for the most complex incidents (Table 3). Alaska and the Eastern GAs used the fewest number of Type 1 IMTs ($n = 6$ and 5, respectively), while the North-west and South-west used the most ($n = 60$ and 43, respectively). The North-west also used the most Type 2 IMTs ($n = 228$). A normalised look at IMT usages revealed that Eastern, Northern California, North-west, Southern California and Southern all exceeded 3 teams per 10 WFDSS fires (range 3.1–5.2). Many of these same GAs also demonstrated high resource capacity in addition to high IMT usage (Hand *et al.* 2017), which may be influenced by risk preference (Katuwal *et al.* 2017).

Are differences in wildfire risk evident at scales finer than the GA?

There is a geography to wildfire risk in the USA at the unit-scale that crosses GA boundaries (Fig. 9). The LQ depicts higher concentrations of the use of high Relative Risk, especially in the Great Basin and adjacent areas dominated by rangeland vegetation types. Higher risk was also evident for BLM and BIA/Tribal lands in the South-west (also dominated by rangeland fuels) relative to USFS forested lands. High risk was less prevalent (LQ < 1.0) in forested units dominated by the USFS (especially wilderness areas) and in NPS jurisdictions in all GAs.

Do the federal land management agencies differ in risk selection?

The NPS used high Relative Risk infrequently compared with other agencies (Fig. 10) and the USFS also favoured low and moderate Relative Risk compared with other agencies. County and local, state and 'other' (primarily federal) jurisdictions invoked high Relative Risk and strongly limited low Relative Risk. Of the federal agencies, the BIA and the BLM used high Relative Risk most frequently. With the exception of the USFS and NPS, all agencies selected low Relative Risk less than the national value.

Discussion

The concept of risk pervades fire decision-making in the USA, in large part because federal policy mandates consideration of the use of fire to maintain and restore ecosystems while simultaneously protecting values at risk, including life and property. Although life and private property are salient to all wildfire objectives, a patchwork of priorities for fire management exist, because the various missions of the federal agencies differentially emphasise protection versus ecosystem values. Almost by default, wildland fire management is set up to be complex in the USA, where many wildfires involve multiple ownerships or jurisdictions.

Despite this complexity, fire managers used the federally mandated the WFDSS risk assessment process on $< 1\%$ of wildfires occurring between 2010 and 2017 (5087 of 616 032), indicating that formal decision support is not used or needed for most wildfires. The remaining 99% of wildfires in the period were either not federal, were suppressed or went out on their own before a formal assessment was necessary. WFDSS fires lasted 20–30 days on average and more than 30% were shared between more than one jurisdiction, suggesting a degree of administrative complexity. WFDSS fires were also dominated by one agency, the USFS ($\sim$60%), indicating a strong influence of this agency on the data.

Notwithstanding the generally complicated nature of these extended attack wildfires represented in the WFDSS, most of the USA favoured low and moderate Relative Risk. The fact that a majority of these long-duration federal wildfires were not considered high risk may be due in part to an absence of values at risk in the areas where the fires occurred (e.g. Value ratings were consistently rated lower than other elements) (Fig. 3) or federal land managers were able to mitigate adverse wildfire effects. Less than 25% of these fires had a high rating for the Value sub-element (i.e. 'proximity and threat of fire to values'),

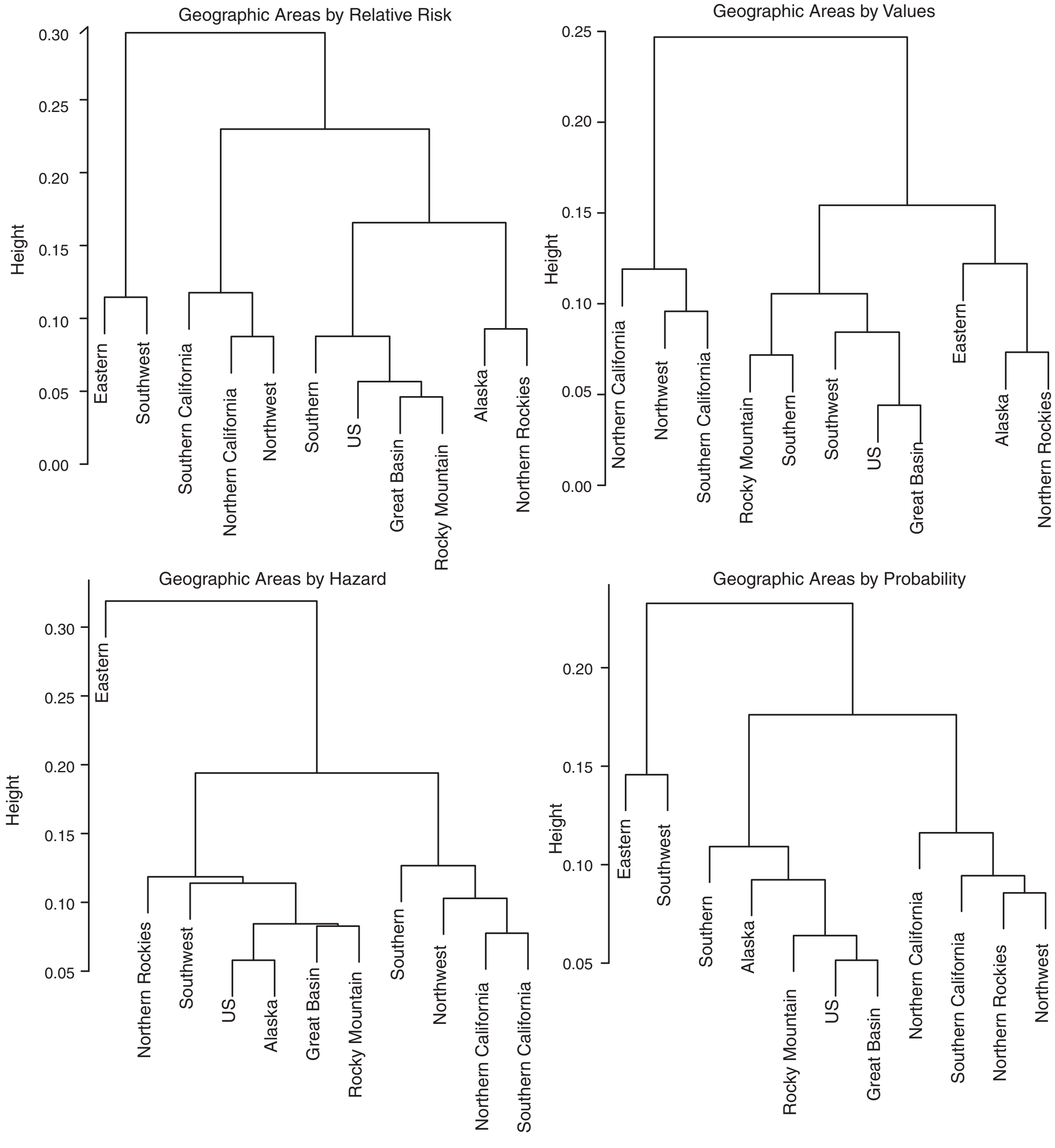

Fig. 7. Dendrograms of Relative Risk from hierarchical clustering of frequencies for each geographic area and the US, by relative risk assessment and by the risk elements of Values, Hazard and Probability.

suggesting that the remaining wildfires either had multiple burn periods for a fire to reach values at risk or posed little threat at all (Fig. 4).

Patterns of risk

Nationally, 38% of long-duration, federal wildfires were rated as high risk, but, at finer scales, the GAs on the West Coast used high risk more than other GAs. These areas are at the epicentre of biophysical risk, with large populations living adjacent to highly flammable landscapes (Ager *et al.* 2013, 2019). In the North-west GA, close to 60% of WFDSS fires were high Relative Risk and > 30% of its fires involved multiple agencies. The region also used high Values, Hazard and Probability more than any other GA. In contrast, the South-west favoured low for fire behaviour (Hazard), resources, threat and concern (Values) and time of season (Probability), which

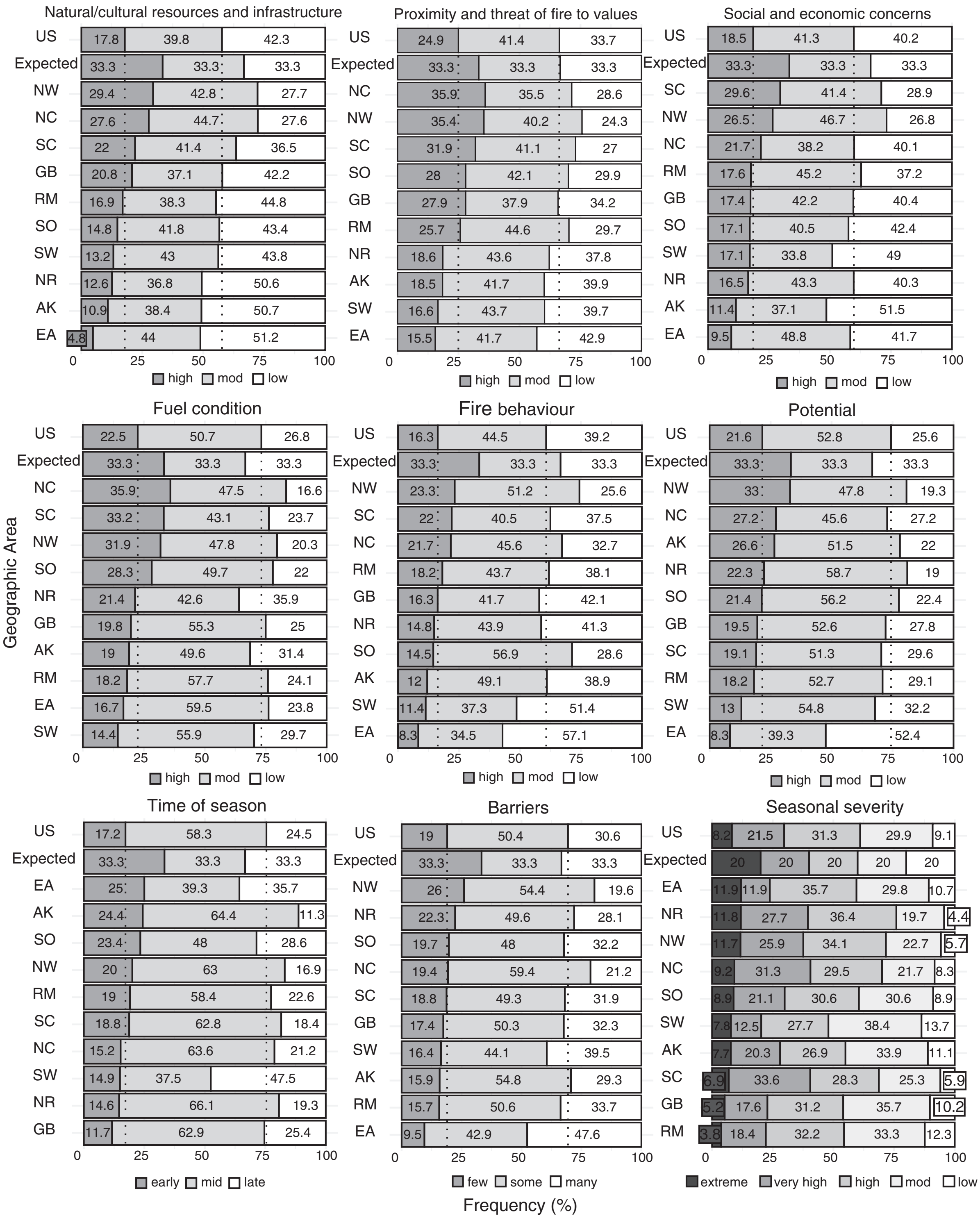

Fig. 8. Frequencies of sub-elements by geographic area (GA). Frequencies of high, moderate and low ratings for sub-elements by GA, the US and expected. GAs include the North-west (NW), Northern California (NC), Southern California (SC), Southern (SO), Northern Rockies (NR), Rocky Mountain (RM), Great Basin (GB), Alaska (AK), South-west (SW), Eastern (EA), the United States (US) and expected. Dotted lines extend from the threshold of high, moderate and low ratings from the US and show how the GA frequencies compare with the US. Value sub-elements, followed by Hazard and Probability sub-elements are shown sequentially.

Table 3. USA federal fire information from the Wildland Fire Decision Support System (WFDSS)

Fire data for geographic areas and the United States summarised from the WFDSS, the Fire Occurrence Database (FOD) and the National Interagency Fire Center (NIFC) from 2010 to 2017

	WFDSS									FOD		NIFC	
	Total (*n*)				Percent (%)					Total (*n*)			
Geographic area	Fires[A]	RRA[B]	Days between start and contained dates	Days between start and controlled dates	Fires[C]	RRA[C]	More than 1 RRA/fire[D]	Mult. Juris.[E]	WFDSS incidents/total fires[F]	Fires[G]	Hectares[G]	Type 1 IMT[H]	Type 2 IMT[H]
Alaska	542	911	41	44.2	10.7	7.4	60.4	48.0	12.6	4300	3 875 773	6	27
Eastern	84	222	12.2	31.3	1.7	1.8	83.8	10.7	0.1	106 079	349 961	5	39
Great Basin	977	2003	15.3	20.4	19.2	16.3	69.9	22.0	4.6	21 201	3 593 896	25	143
Northern California	217	903	17.1	29.1	4.3	7.3	90.9	34.6	0.7	30 277	1 079 286	30	79
Northern Rockies	802	1562	36	43.7	15.8	12.7	68.5	22.6	3.5	23 091	1 762 418	35	122
North-west	649	1813	28.5	40.4	12.8	14.7	84.8	32.7	2.3	28 544	2 891 425	60	228
Rocky Mountain	478	1183	15	23.9	9.4	9.6	77.9	30.3	0.9	54 856	1 381 721	23	70
Southern California	304	1313	21.6	32	6.0	10.7	91.3	38.8	0.9	33 212	967 395	28	79
Southern	304	799	12.7	22.4	6.0	6.5	81.7	23.7	0.1	275 143	3 143 929	33	60
South-west	730	1615	17.2	24.8	14.4	13.1	74.6	18.4	1.9	39 329	3 817 136	43	79
USA	5087	12324	22.8	31	100.0	100.0	77.4	27.9	0.8	616 032	22 862 939	288	926

[A]Fires represent wildfires in the WFDSS with at least one completed RRA.
[B]RRA represents the total number of completed RRAs per wildfire incident.
[C]Percent fires is the total number of fires (with a completed RRA) per GA divided by the 'US', similarly done for the percent RRA.
[D]More than 1 RRA/fire is the percent frequency that an individual WFDSS wildfire had more than one RRA, a measure of the usage of the RRA in the WFDSS.
[E]Mult. Juris. is the percentage of WFDSS wildfires that involved more than one jurisdiction, an indicator of higher complexity.
[F]'WFDSS incidents/total fires is the proportion of WFDSS wildfires to the total record of all wildfires as recorded from the FOD (Short 2017) for the years 2010–2017 and is a measure of WFDSS use.
[G]Fires and hectares (1 ha = 2.47 acres) from the FOD for the years 2010–2017 reflect all wildfires, not just federal fires.
[H]Type 1 incident management team (IMT) and Type 2 IMT are from the National Interagency Coordination Center yearly statistics and summary data for the years 2010–2017 and are also indications of complexity and costs.

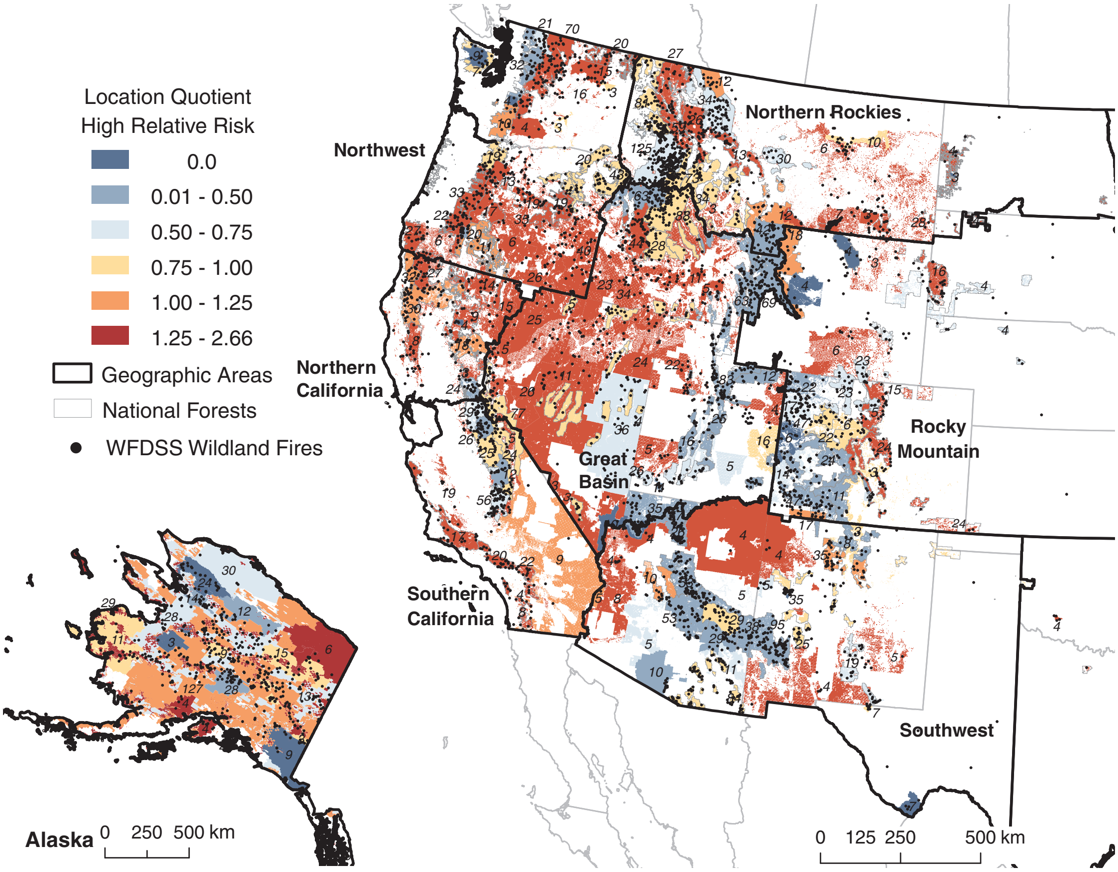

Fig. 9. Concentrations of high Relative Risk in the western USA from the location quotient for federal jurisdictions with at least three WFDSS fires and an average of 24 fires.

translated into low ratings for all of the main risk elements, especially Values, and resulted in low and moderate risk for 76% of its fires. The South-west likely benefits from the occurrence of the North American Monsoon, which provides a semi-predictable end to its primary fire season during the month of July (Sheppard *et al.* 2002), and its flammable mountain ranges are usually isolated by inflammable deserts in all but the wettest of years. The scales of these temporal and spatial 'barriers' are fundamentally different from what occurs in the North-west GA, perhaps giving managers at least the perception of more certainty (and less risk) in the future of evolving wildfires, which is a topic for future exploration.

Patterns in wildfire risk were also evident at finer scales (Fig. 9) across GA boundaries. The LQ showed how some jurisdictions selected high risk more than the national value, along shared GA boundaries, such as between the Great Basin and North-west GAs. The role of more complex fire management considerations in these areas, such as rangeland vegetation, cattle grazing, fast-moving fires and the expansion of invasive annual grasses, managed primarily by the BLM, are worthy of further exploration. These traditional multi-use areas are dissected with range allotments for cattle grazing or private lands interspersed among federal lands, especially along historic railroad corridors where land was provided to corporations and states through land grants to encourage development and westward migration in the middle of the 19th century (*Pacific Railroad Act 1862* – an act to aid in the construction of a railroad and telegraph line from the Missouri river to the Pacific ocean, and to secure to the government the use of the same for postal, military, and other purposes). Ecological and social challenges related to federal land use juxtaposed with the preservation of highly flammable sage grouse rangeland habitat, an indicator species of the sagebrush rangelands endemic to the Great Basin, may also be a factor (Wisdom and Chambers 2009; Shinneman *et al.* 2018).

The BIA lands are often associated with high Relative Risk. Many reservations are located in rangelands and drier forests, property is widely dispersed within them and there is often a reliance on timber and grazing assets to support local economies. Among all agencies, jurisdictions associated with dry forest types used high Relative Risk more than the national value, notably in the Eastern Cascade mountain range in Washington and the Southern Cascades in Oregon and California. These tendencies were different for the dry forests in the South-west, which used high Relative Risk less than the national average and are managed primarily by the USFS. Concentrations of high risk also occurred in national forests adjacent to communities, as seen in the Rocky Mountain and Northern Rockies GAs, where lower use of high risk was evident in backcountry areas and wilderness.

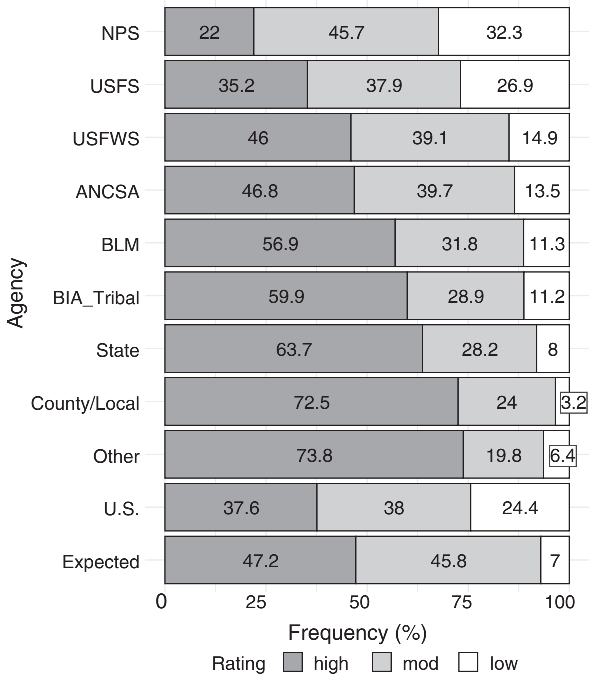

Fig. 10. Relative Risk by agency, including summaries for the five federal land management agencies (NPS, USFS, USFWS, BLM, BIA/Tribal), non-federal (State, County/Local) and 'Other' agencies including the Department of Defence, Bureau of Reclamation and Army Corp of Engineers. A summary of ratings for the collective USA and what is 'Expected' due to chance are included for comparison. ANCSA, Alaska Native Claims Settlement Act; BIA, Bureau of Indian Affairs; BLM, Bureau of Land Management; NPS, National Park Service; USFS, USA Forest Service; USFWS, U.S. Fish and Wildlife Service.

The different missions of land management agencies may also be contributing to patterns of risk. The NPS mission emphasises conservation, which perhaps favours greater risk tolerance in achieving natural outcomes. For instance, Crater Lake National Park located in the southern portion of the North-west GA and Lassen National Park in the north-east portion of the Northern California GA are islands of lower risk in relation to the national forests surrounding them ($LQ < 0.50$). Past fires in these areas may also contribute to perceptions of lower risk in the form of natural barriers to fire spread. Similar patterns emerged in the central Sierra Nevada mountains in California, especially the NPS jurisdictions of Sequoia-Kings Canyon and Yosemite National Parks, two of the original locations where prescribed natural fire was introduced in the late 1960s (van Wagtendonk 1995). Physiographic characteristics amenable to low risk (high-elevation, rocky terrain, moist forest types etc.) for some NPS units may also be a contributing factor to the less frequent use of high Relative Risk.

Similarly, USFS lands with a strong wilderness presence tended to use high risk less frequently. The *Wilderness Act* of 1964 designated wilderness as lands for protection and preservation in their natural condition, similar to the conservation emphasis of the NPS mission. The traditional use of wildfire to maintain natural conditions in wilderness areas may be contributing to the selection of less high risk, as seen in the Selway-Bitterroot and Frank Church wilderness (Great Basin GA) and the Bob Marshall, Great Bear and Scapegoat wilderness areas in the Northern Rockies (Dale 2006; Collins and Stephens 2007; Collins *et al.* 2009; Miller *et al.* 2012; Larson *et al.* 2013; Hunter *et al.* 2014; Parks *et al.* 2014; Boisramé *et al.* 2017).

Overall, the patterns of risk identified in this research were likely caused by a complex mix of biophysical factors, infrastructure and community development patterns, agency missions and regional fire culture. Direct causal explanations are obscured by the variability of these factors within GAs. Although it is likely that the fire environments of the North-west and Northern California tend to produce more higher risk fires than the South-west, due to higher density of Values at risk, proximity of fire to Values at risk, less certainty in future weather, longer duration events, higher fuel loads and more continuous fuels, it is also likely that cultural differences among fire managers play a role. In a previous study of USFS decision-makers (Cortner *et al.* 1990), patterns of risk tolerance were reported by GA, matching patterns found in our study. In this study, the South-west and Great Basin GAs were higher risk-takers while California and the Pacific North-west were more risk averse, consistently selecting low-risk/high-expense options from a range of hypothetical planning scenarios. Risk avoidance was influenced most strongly by safety, values/resources at risk, public opinion and the reliability of information. The commonality in patterns between those of Cortner *et al.* (1990) and ours suggests that some of the regional differences in risk perception identified almost 30 years ago may still persist.

A tendency when examining patterns of risk from operational assessments is to wonder what the real risk is. This tendency implies the existence of objective risk that managers might not know or do not use. We argue that the RRA is real risk because it is driving strategic responses on wildfires. We suspect that disparities exist between risk from the RRAs and the various quantitative wildfire risk assessments (QWRAs) used for land management planning and this is the subject of future research. Although risk has been assessed systematically at the national scale in the USA (Calkin *et al.* 2010; Scott *et al.* 2013; Ager *et al.* 2019), the QWRA is applicable at spatial and temporal scales that may be incompatible with the RRA and most useful during pre-fire planning phases when actual ignition locations are unknown. The QWRA applies burn probabilities simulated from random or historical ignition locations to estimate ranges of fire behaviour from historical weather and wind data; however, these estimates become less useful to address the finer-scale temporal or spatial fuels, weather and fire behaviour once an ignition location is known. The QWRA may also miss the breadth of Values at risk for a specific fire as discerned by a land manager in favour of spatially consistent cadastral records (Hollingsworth and Panunto 2018). Applying QWRA pre-fire planning information to evaluate real-time, operational wildfire risk in the RRA presents a challenge for future work and additional efforts to leverage risk management assistance products such as exceedance probability curves to help prioritise wildfires for multi-agency coordination groups during periods of heavy wildfire occurrence is a start to bridging quantitative and operational risk (Scott and Thompson 2015; Schultz *et al.* 2021). Ultimately, this equates to responding to wildfire ignitions using the best available information and tools that allow fire to be part of ecosystems while protecting life and property.

Conclusion

This research explored patterns of wildfire risk at different scales and among land management agencies. High risk was more prevalent in the western USA than any other region when incident-specific RRAs from the WFDSS were summarised from 2010 through 2017. High risk was also more common for the BIA, BLM, State, County/Local and other non-land management agencies (i.e. Department of Energy or Defence). In many locations across the USA there was a disparate use of high risk between adjacent jurisdictions, which warrants further exploration of the biophysical, cultural and other factors driving these differences between seemingly similar geographic locations.

The drivers of risk perceptions that manifest during wildfire events is a topic of further study and may help policy makers better allocate resources to address local-level fire management concerns. Some locations may benefit from increased support for working with communities to better prepare for fire (e.g. locations where both social concerns and resources and infrastructure are rated high). Other locations may benefit from closer examination of landscape barriers and how they spatially connect to create contingency lines (e.g. locations where barriers are rated as numerous or low). The influence of risk perceptions on the selection of fire management strategies also warrants further exploration to understand why some jurisdictions use a range of fire management strategies compared with a preference for suppression strategies. Managing naturally ignited wildfires to achieve ecological and restoration objectives is allowed for some federal lands and is part of the larger federal wildland fire management goal of increasing the resiliency of communities from wildfire (USDI/USDA 2014; Christiansen 2018).

By illuminating patterns of risk by GA, agency and unit, we sought to encourage discussion regarding how risk is characterised across the USA and where additional investments in tools and training might be targeted. This is the first formal summary of risk data housed in the WFDSS and although numerous DSS exist globally, the ability to summarise patterns of risk over a reasonably long period of time is unique to the WFDSS. Risk patterns can provide insights into the factors that are influencing local decision-making and may provide opportunities to directing resources and research to where it is needed most.

Conflict of interest

The authors declare no conflicts of interest.

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